ARIZONA DEPARTMENT OF TRANSPORTATION

REPORT NUMBER: AZ92-344

DEVELOPMENT OF SEISMIC ACCELERATION CONTOUR MAPS FOR ARIZONA

Final Report

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16. Abstract This report documents the research, field investigations and analyses used to compile a fault map and seismic acceleration coefficient contour maps for Arizona. The seismicity of adjacent regions which may potentially impact Arizona are factored into the analysis. Potential earthquake sources were evaluated using ground and airborne geological reconnaissance, photogeological interpretations and subsurface explorations of selected representative fault features. One hundred eighty-six faults or fault zones are identified. These data combined with other geological, seismological and geophysical data define twenty-one seismic source zones influencing Arizona.

Earthquake recurrence relations for each seismic source are derived. Energy release relationships based on slip rates and seismic moment are evaluated. Comparisons with recurrence relations defined by other researchers such as Algermissen, et al (1990) are made. The SEISRISK III computer program is used to conduct a probabilistic analysis to define acceleration coefficients with 90% probability of non-exceedance in 50 years in accordance with AASHTO seismic design guidelines. Additional maps for 90% probability of non-exceedance in 250 years and for peak ground velocity were also prepared.

Ground acceleration coefficient (90-percent non-exceedance in 50 years) levels determined from the research program are higher than those in the existing AASHTO Seismic Guide specification in the northwestern and north-central parts of the state due to the significant number of potentially active faults identified in those regions. Coefficients are also higher in the southwest corner of Arizona due largely to California and Mexico source zones with high recurrence rates. Ground accelerations in the southeastern part of the state are significantly lower than previous estimates. Acceleration levels are essentially comparable to AASHTO guidelines in the remaining parts of the state.

Maps of new seismic acceleration coefficient contours and compiled faults in Arizona have been prepared to a scale of 1:1,000,000. Electronic digital data files are compiled in a format that can be used to support site-specific and regional studies for seismic design. The map of horizontal acceleration with 90-percent probability of non-exceedance in 50 years is recommended to the Arizona Department of Transportation for use in AASHTO-based design of highway bridges.

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PREFACE

This research program was funded by the Arizona Department of Transportation, Arizona Transportation Research Center. The report was prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration, Region 9.

SI* (MODERN METRIC) CONVERSION FACTORS

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9	ARIZ.	HPR-PL-1(37)344	FWHA-AZ92-344

APPROXIMATE CONVERSIONS TO SI UNITS

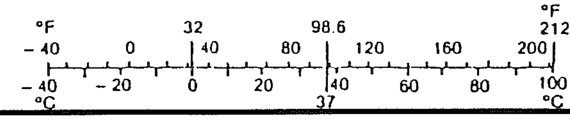
SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	millimetres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

***NOTE:** Volumes greater than 1000 L shall be shown in m^3.*

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
ML	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8C + 32	Fahrenheit temperature	°F



*SI is the symbol for the International System of Measurement (Revised April 1989)

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1. INTRODUCTION

a. Purpose and Objectives

This report describes the methods and results of a year-long research project to evaluate seismic hazards in the state of Arizona and to produce a new seismic acceleration contour map to be used in the design of Arizona Department of Transportation (ADOT) facilities. The work was performed by the geological and engineering consulting companies of Geological Consultants of Phoenix, Arizona and Earth Mechanics Inc. of Fountain Valley, California under the direction and guidance of the Transportation Research Center of ADOT.

The investigation comprised six basic tasks:

1) literature review,
2) identification of seismic source zones and faults,
3) preparation of seismic source zone and fault location maps,
4) location of seismic acceleration coefficient contours,
5) preparation of seismic acceleration contour maps, and
6) documentation of methods and results.

The methods employed and the results of these tasks are discussed and described in this report.

b. <u>Background</u>

In 1981, the Applied Technology Council (ATC) published a Federal Highway Administration Report (FWHA/RD-81/081) "Seismic Design Guidelines for Highway Bridges". The 1981 ATC report was adopted by AASHTO and implemented in the AASHTO Guide Specifications for Seismic Design for Highway Bridges (AASHTO, 1983). The document was later adopted as the AASHTO Standard Bridge Design Specification for Bridges (Buckle, 1991) and is currently used by most State Highway Departments for seismic design of highway bridges. The AASHTO Seismic Guide Specification contains a seismic acceleration coefficient contour map of the United States. The acceleration coefficients from this contour map serve as anchor points at zero-second period for the design response spectrum curve in the AASHTO specifications.

The seismic acceleration coefficient contour maps for bridge design have evolved to incorporate more up-to-date research in earthquake hazard studies. The latest map adopted by the AASHTO subcommittee for seismic design of bridges (Buckle, 1991) is the contour map of Horizontal Peak Ground Acceleration for a Probability of 90-percent non-exceedance over a 50-year duration developed by Algermissen et al (1990).

An objective of this project is to incorporate more-recent and/or more-refined local geological and seismological data into the design of highway facilities while preserving the underlying design criteria of the national AASHTO coefficient map. The principal differences between the new seismic acceleration contour maps developed from this project and the AASHTO national map emanate from the more detailed and up-to-date geological and seismological data compiled and acquired in the course of the project.

c. <u>New Seismic Acceleration Coefficient Contour Maps</u>

The new seismic coefficient contour maps are presented as Plates 2a through 2d of this report. Plate 2a presents the horizontal peak ground acceleration (PGA) contour map with 90-percent probability non-exceedance in 50 years, and it is recommended for use in bridge design by ADOT. The other maps (250 years and A_v maps) were developed so comparisons can be made to other maps developed in prior studies such as Algermissen et al (1990). The probabilistic model and computer program used to produce the new maps are similar to those used for previous maps. In contrast to previous ground-motion contour maps, the new maps are heavily based on detailed geological investigations within and adjacent to the state of Arizona.

Over the past few decades, a substantial body of new data on the location and activity rates of faults in the Arizona region has become available. The present maps are a direct reflection of these new data but also reflect a somewhat different approach to how seismic hazards are defined and how data are incorporated into the evaluation. Most previous seismic-hazard investigations concentrated on historical seismicity with only limited consideration of major late-Quaternary-age faults. These methods may be adequate for areas where the rate of tectonic activity is high (for example, western California), but in an area such as Arizona where rates of tectonism are very slow, the occurrence of just a few new earthquakes can greatly change the makeup of maps based only on earthquakes. To characterize the seismic potential more completely, a much broader perspective is necessary. This is clearly demonstrated by the poor correlation of historical earthquakes to specific late-Quaternary faults in Arizona. By examining only Quaternary faults or only earthquakes, the potential for future earthquakes cannot be characterized with much certainty. By examining both factors, the understanding of seismic potential is improved, but it may still be lacking in some aspects, as shown by the occurrence of major earthquakes throughout the world where there is no seismicity and no well-known late-Quaternary faults.

To minimize the occurrence of "surprise" earthquakes such as those that occurred in central California (Coalinga) and Idaho (Borah Peak) in 1983, and in the Los Angeles, California area (Whittier) in 1987, this investigation included a broad spectrum of geologic and seismologic data and techniques. For example, instead of using just Holocene-age or late Quaternary-age faults, all faults that have been active during the present tectonic regime (neotectonic) were considered in the analysis. These neotectonic faults were used to define seismic sources capable of generating earthquakes, and then were used to help quantify the seismic potential. Instead of relying solely upon the incomplete historical earthquake record, this investigation directly applied the relatively new geological data on prehistorical earthquakes generated from detailed geomorphic, trenching, and field investigations, to the quantification of earthquake recurrence relationships.

Another important aspect of this investigation is the method of implementation and promulgation of results. The final products are submitted in computer format such that they can be modified and reproduced by ADOT computers at any scale by using readily available computer software such as AutoCAD.

d. Report Organization, Terminology, and Format

The report is organized somewhat in chronological order of the various tasks that were performed.

Measurements within the report are generally in the English system (inch-feet-miles). However, many of the computer programs and mathematical formulae employed in the analysis require units expressed in the metric system; rather than convert all numbers back and forth between the two measurement systems, it is preferable to leave some numbers expressed in the metric system. For example, faulting slip rates are given in millimeters per year (mm/yr). Rates of geologic (tectonic) processes in Arizona are generally very slow, commonly hundredths and thousandths of a millimeter (10^{-2} and 10^{-3}). Such rates are manageable when expressed in mm/yr but as fractions of inches they would be difficult to relate to, even when one is more familiar with the English system.

We attempted to keep esoteric geological terms to a minimum, but to keep discussions as short as possible and the report focused on the important issues it is necessary to use some well-established geological terms. To help the reader through these discussions, a glossary of selected geological terms used in the report is provided as Appendix B.

Similarly, geological ages are frequently used in the discussions. Appendix C provides a geological time scale to help the reader conceptualize some of the great time spans involved in geological processes as discussed in the report.

e. Participants

Principal participants and their roles in the research project are shown on the project organization chart on Figure 1.

f. Acknowledgements

A project of this magnitude requires the cooperation of numerous individuals both within the project framework and from the geological, seismological and engineering communities at large. Many colleagues, too numerous to mention, contributed by sharing their unpublished work, their opinions, insights and constructive criticism, and we are very grateful. Some particular individuals who contributed were Mr. Larry A. Scofield, P.E., Manager, and Mr. Yee J. Ho, P.E., Project Manager, of the Arizona Department of Transportation Department, Transportation Research Center. Special thanks are also extended to other ADOT representatives including Mr. Charles Deutschlander, Mr. Richard LaPierre and Mr. Mike Hall (Photogrammetry and Mapping) who provided aerial photographs, as well as highway location data,

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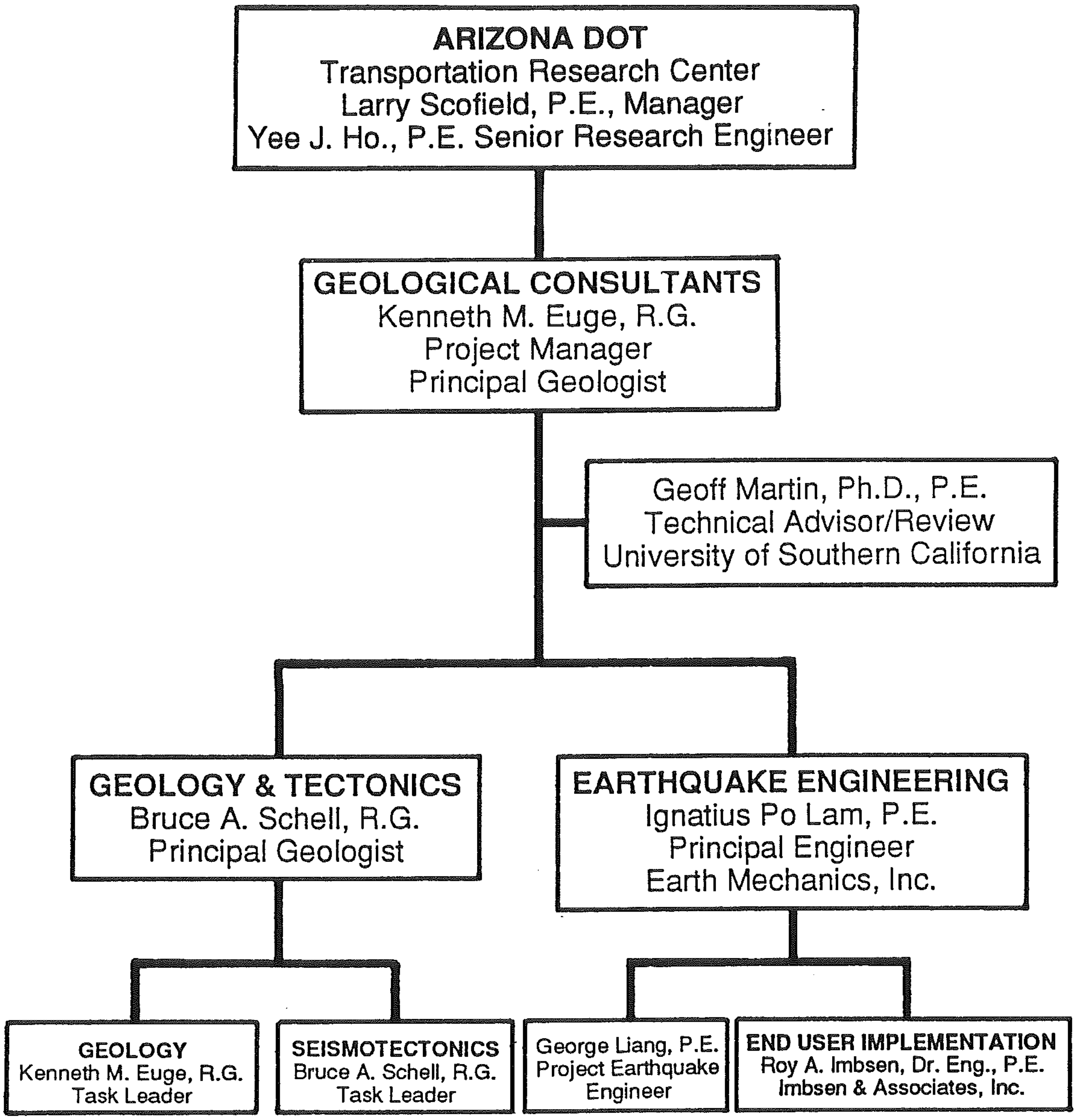

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FIGURE 1
PROJECT ORGANIZATION CHART

and to Mr. Scott Hutchinson (Transportation Planning) who provided the ADOT digital line data files used in base map preparation.

Appreciation is due to Ms. Diane Crawford of the Arizona State Land Department who helped expedite the right-of-entry application required for exploration of the Aubrey Fault. Special thanks are extended to Mr. Merwin Davis, owner of the C.V. Ranch who allowed us access to his land for the Big Chino fault field studies. Mr. Davis' interest and cooperation was most helpful and the people of Arizona are indebted to him.

The valuable technical support of various colleagues, researchers and professionals in the field of geology, seismology and earthquake engineering is acknowledged and appreciated. Special thanks is given to Dr. Larry Fellows and Dr. Phil Pearthree of the Arizona Geologic Survey, Dr. David Brumbaugh of Northern Arizona University, and Dr. David Perkins of the U.S. Geological Survey.

The research team is also indebted to Ms. Sally Atkinson and Ms. Mary Peters for their rapid response, attention and resolution of contract administration matters during the term of the project.

2. LITERATURE REVIEW

a. Scope of Work

The principal scope of work for the literature review task was to review all pertinent geological literature and available unpublished reports and data, and to compile a working data base for the remaining project tasks. Literature and data were compiled from a wide variety of sources including government agencies, local libraries, utility companies, and personal libraries of the research team. This task also included personal contact with geoscientists familiar with the geology and seismology in the area. Pertinent data were compiled and summarized onto maps, tables, and work sheets. The extent and results of these efforts are described further in the subsequent sections of this report.

Although the majority of available information had been collected early in the investigation, data compilation, refinement, and analyses continued throughout the entire project. The investigators evaluated the reliability of most of the data collected and the most reliable data were used throughout the project. Some of the collected data were adequate as they existed but more data were needed for several aspects. The additional data were generated by the principal investigators and the rest came from further discussions with other geoscientists or by more-detailed analysis of the existing literature.

b. <u>Data Collection</u>

The principal type of information needed for this study were data on faults and earthquakes. The literature base that contained the needed information was large and diverse. To keep track of the large amount of data, information was compiled in two formats: 1) data sheets and 2) maps. The final maps of geologic faults is presented as Plate 1. This map shows the location of faults and identifies each fault with a unique reference number. Data on each fault were compiled on fault data sheets. Summaries of the most pertinent data from these data sheets are included in Appendix A.

The principal sources of data and information were:

- State and federal agencies such as the Arizona Geological Survey, Arizona Earthquake Information Center, U.S. Geological Survey, U.S. Bureau of Reclamation, and Utah Geological and Mineral Survey;

- Universities and colleges such as the University of Arizona, Arizona State University, Northern Arizona University;

- Scientific and engineering journals such as the Bulletin of the Geological Society of America, Seismological Society of America Bulletin, and American Society of Civil Engineers Journal;

- Utility companies such as Arizona Public Service Company, Arizona Nuclear Power Project, Southern California Edison Company, San Diego Gas and Electric Company, Salt River Project;

- Scientists and engineers presently conducting research on faults, seismicity, seismic zoning, and earthquake engineering; and

- Special publications such as Arizona Geological Society Digest and various geological society field-trip guidebooks.

3. FIELD INVESTIGATIONS

The field investigations consisted of four principal tasks, photogeology, aerial reconnaissance, ground reconnaissance, and fault trenching.

a. Photogeology

The photogeology task involved detailed and regional evaluation of selected areas. The detailed studies used primarily stereo, black and white, aerial photographs at scales of between about 1:40,000 to 1:60,000. The photographs were obtained from the Arizona Department of Transportation Photogrammetry and Mapping Division. The black and white photographs were augmented with limited color satellite images and photographs.

The aerial-photograph analysis involved documenting geologic features such as faults, folds, lineaments, stratigraphy, and uncertain features. The aerial photographs were used to help identify areas that would yield reliable information on age and rates of neotectonic activity. Interpretations were plotted on 9 by 9 inch mylar overlays taped to alternate photographs. These overlays were also freely annotated with any pertinent information that might help identify significant features during the aerial and field reconnaissance, and with questions that needed to be answered by field checking, field measurement, or aerial reconnaissance. The annotated aerial photographs were then strategically arranged in portable files so as to provide easy and rapid retrieval during the aerial and field reconnaissance.

The aerial photograph interpretations were conducted in stages at various times depending on the nature of questions and the difficulty in the resolution of questions. For example, based on our review of literature, the Mesa Butte area was identified as an area that could provide important data. The first field visit indicated that features needed to be mapped in more detail and over a larger area than was available by published data. Also, better control over relative age data was needed for lava flows displaced by faults. A determination was made that further aerial-photograph analysis would provide the best information, and more photographs were obtained. Further aerial photograph interpretation then resulted in identification of areas where the best or most representative field measurements could be made. These areas were verified and looked at in more detail during the aerial reconnaissance which also provided information on the best access roads to the specific areas. Then the aerial photographs were taken to the field during a second field visit and the identified areas and features were measured, mapped, and otherwise documented in more detail, in the field at the outcrop. Upon return from the field, additional interpretations or refinements of previous interpretations were made under the more-controlled conditions of the office (i.e. better lighting, no wind, rain, etc).

The aerial-photograph analysis and aerial reconnaissance revealed that few of the faults in Arizona occur in areas with young deposits of Quaternary age. The paucity of Quaternary strata rendered trenching studies unsuitable for most faults. This made evaluation of ages of fault displacement and recurrence intervals very difficult. Instead of trenching, aerial-photograph and geomorphic analyses were found to provide the best results considering the time and budget constraints of this project.

b. Aerial Reconnaissance

Aerial reconnaissance of preselected areas was conducted on 5, 6, and 7 of September 1991. The reconnaissance was by single engine, fixed-wing light airplane with overhead wing without wing struts. Such aircraft are especially well suited for large regional investigations such as this because they provide good visibility, speed, and long range. The aerial reconnaissance concentrated on faults and features identified during the literature review, preliminary aerial photograph-interpretations, and some preliminary field reconnaissance. Maps and aerial photographs which had been previously annotated in the office with questions to be answered about certain features were taken along and used for keeping track of locations and data. Documentation of data during the flyover was by notes on trip logs, aerial photograph overlays, maps, VHS-format video photography, and by 35 mm photographs in both print and transparency format.

The flights departed Phoenix Sky Harbor International Airport at about sunrise. Routes were planned so the areas of interest could be viewed under optimum lighting conditions. The best time for viewing areas with little relief is generally during the early morning when the sun angle is low and shadows accentuate otherwise subtle or obscure fault scarps. The best time for the canyon areas is mid day when the sun is high and illuminates deep into the canyons. Visibility was adequate but commonly less than ideal for photography due to atmospheric haze, low clouds, and air turbulence. Figure 2 shows the flight paths for the three successive flights. The illustrated flight paths are very generalized. In actuality, the flights were very irregular with frequent course deviations, multiple circling, and back and forth trips to view certain features from various angles, altitudes, and lighting conditions (i.e. morning, mid day, afternoon). Upon return from the flight, the photographs were immediately processed and then annotated with notes and station numbers.

c. Ground Investigations

The ground field investigations consisted of visits by the project geologists to areas of some particular interest. This activity was conducted during several visits generally lasting a few days (5 to 7) during the months of July through December, 1991. Field visits were made at various stages of the investigation depending on the nature of the features or areas to be visited, and on the timing of other activities. Some field checking was conducted during the literature review stage, other features were checked after the aerial flyover, and others after aerial-photograph interpretation. Because most of the areas requiring field checking were in remote areas and generally required travel on primitive dirt trails during rain squalls, four-wheel-drive vehicles were used for transportation. Activities during these visits comprised general reconnaissance, verifying aerial-photograph interpretations, geological mapping, and fault-scarp morphology analysis.

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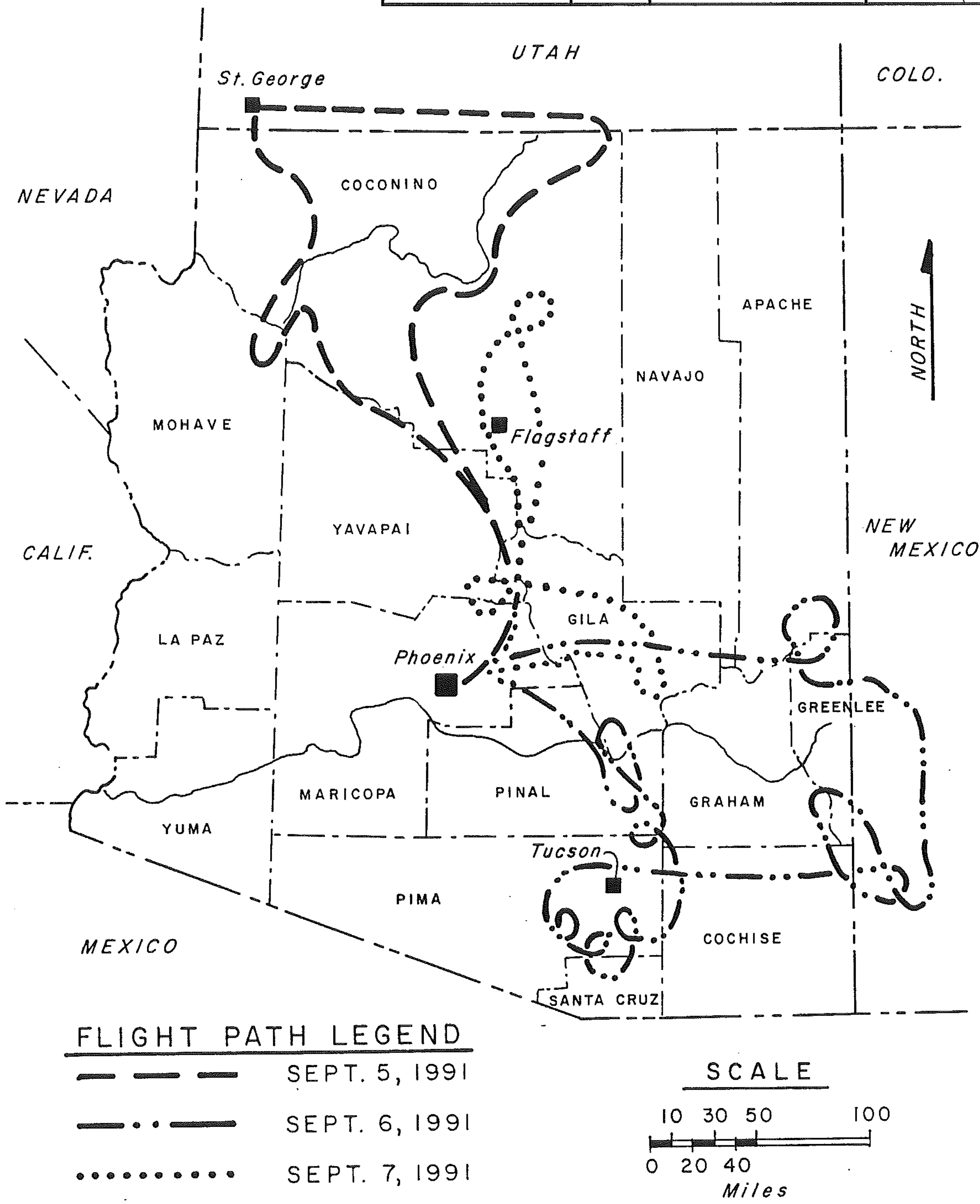

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FIGURE 2

AERIAL RECONNAISSANCE FLIGHT PATH MAP

Features of interest were documented in field notes, maps, and 35 mm photographs. 35 mm photographs were commonly taken in stereo pairs to provide three-dimensional views for future analysis during office work and for detailed comparisons with aerial photographs.

Most of the ground field investigations were conducted in an area extending from the northwest corner of the state to the Tucson area. This is the area with the most young faults and perhaps the least studied. Extensive field checking was conducted in the Aubrey, Big Chino, and Verde valley areas, and the area between the San Francisco Peaks and the Little Colorado River (hereafter referred to as the Mesa Butte area).

Other areas receiving more general reconnaissance-type visits were:

- Arizona-Nevada border area
- Hualapai-Detrital Valley area (northwestern Arizona; Bullhead City-Kingman area to Hoover Dam area),
- Northern Kaibab Plateau (Grand Canyon to Utah border), and
- Northern Toroweap/Hurricane faults area.

Areas such as the central Colorado Plateau did not require any special ground investigations because there is no indication of young faults in that region. The Sonoran Desert and eastern California also were not investigated in detail because they had been looked at in detail by the project geologists and by the Arizona Geological Survey, many times in past few years for various projects, thus, up-to-date information on those areas was already in hand. Data from southeastern Arizona was available from aerial photographs and aerial reconnaissance, and from published and unpublished investigations by the University of Arizona, Arizona Geological Survey, and the U.S. Geological Survey who investigated that area in detail in recent years.

In addition to the areas investigated by fault trenching, other areas receiving substantial geologic and geomorphological analysis during the ground reconnaissance phase were the Mesa Butte and Verde Valley areas. These investigations are described below:

(1) **Mesa Butte Faults**

(a) **Background:** The criterion of using neotectonic faults (late-Pliocene to present) in seismic source evaluations and seismic hazards analysis is problematical, especially for the Colorado Plateau of Arizona which virtually has no stratigraphic deposits younger than Cretaceous (more than about 100 million years old) in the areas where faults are mapped. Due to this lack of young strata, radiometric and stratigraphic age constraints on faulting are rare. In the absence of dateable materials, the ages of many faults were based on geomorphic expression, that is, if a fault has a prominent, linear escarpment such as that shown on Figure 3, it is considered to be a neotectonic feature. To test whether this is a reasonable approach, a detailed evaluation of faulting in the north-central Arizona area just north of San Francisco Mountain was undertaken. This area, referred to as the Mesa Butte area after the longest and most prominent fault in the area (#104), was selected because it has numerous prominent faults in Paleozoic

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WHITE ARROWS ARE ON THE UPLIFTED BLOCK. LENGTH OF FAULT SHOWN IS ABOUT 6 MILES LONG. OFFSET ROCKS AT GROUND SURFACE ARE PERMIAN-AGE KAIBAB LIMESTONE.

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FIGURE 3

AERIAL PHOTOGRAPH OF ROSE WELL FAULT

and Mesozoic strata which are overlain by dated or correlatable late-Tertiary and Quaternary volcanics (Figure 4). The premise is that if the age of the faults in the Mesa Butte area could be determined, they would provide guidance, by analogy, for estimating the age of faults where stratigraphic age control is lacking.

(b) Methods: Field investigations in the Mesa Butte area consisted of ground checking, aerial reconnaissance, and aerial-photograph analysis. Ground checking included mapping, geomorphic analyses, measuring fault displacements and documenting stratigraphic and age relationships. Geomorphology analyses consisted mainly of assessing the total fault displacements, number of displacements, and displacement per event.

Plate 1 illustrates the great number of surface faults in the Mesa Butte area where there are more than 100 fault zones within a small area of about only 800 square miles. These faults displace Paleozoic and Mesozoic bedrock and several overlapping Quaternary-age volcanic flows. The ages of the volcanic rocks provided important information on the faulting history and thereby helped assess earthquake potential.

Available age information was obtained from published sources. Although there are a large number of age determinations for the San Francisco volcanic area, data in the Mesa Butte area (where faults are most prominent) are relatively scarce. However, with a few key dates such as those of Baksi (1974), Damon et al (1974), and Wolfe et al (1987), a chronology of volcanism

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FAULT COMPRISES TWO PARALLEL FAULTS (INDICATED BY LARGER WHITE ARROWS) WITH DOWNDROPPED CENTRAL GRABEN. LIGHT GRAY ROCKS ARE PERMIAN-AGE KAIBAB LIMESTONE; DARK GRAY ROCKS ARE PLEISTOCENE (1.4 MILLION YEARS OLD) LAVA FLOWS WHICH ARE OFFSET BY A NORTHWESTERLY TRENDING GRABEN (SMALLER WHITE ARROWS) THAT DOES NOT APPEAR TO OFFSET MESA BUTTE FAULT. LENGTH OF FAULT ON PHOTOGRAPH IS ABOUT 6 MILES LONG.

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FIGURE 4

AERIAL PHOTOGRAPH OF MESA BUTTE FAULT

and faulting was developed using geomorphology of cones and flows and the geologic principles of stratigraphic superposition and cross-cutting relationships (Figure 5).

A key volcanic unit in the area is the Tappan Wash (TW) basalt flow. The TW flow has a potassium/argon (K/A) age of 530,000 +/- 79,000 years (Damon et al, 1974; Wolfe et al, 1987). The flow is a narrow sinuous feature (Figure 6) that flowed northward, almost like water, from a vent on the east side of Kendrick Peak south of Highway 180 (Wolfe et al, 1987). The TW flow followed existing stream channels and fault troughs, through the Mesa Butte area to the Little Colorado River north of Highway 64, a distance of about 40 miles. There are numerous fault scarps and other lava flows along the flow path. Some of these features were overrun by the TW flow whereas others deflected the flow indicating that they were already well-developed by the time the flow occurred (Figure 6). Other features displace or overlie the Tappan Wash flow showing that they are younger. Another young flow in the area is the SP Crater flow which has been dated at about 71,000 +\- 4,000 years (Baksi, 1974). The SP flow also flowed across faults and older volcanic flows (Figure 5), some of which are the same features that are overlain by the TW flow. Relative ages were estimated by comparing the geomorphic development (preservation of primary flow forms, amount of erosion, soil cover, vegetation, etc), stratigraphic position, and cross-cutting relationships of the common features.

(c) Observations: Some important relationships and conclusions that provide important insights on the history and rates of

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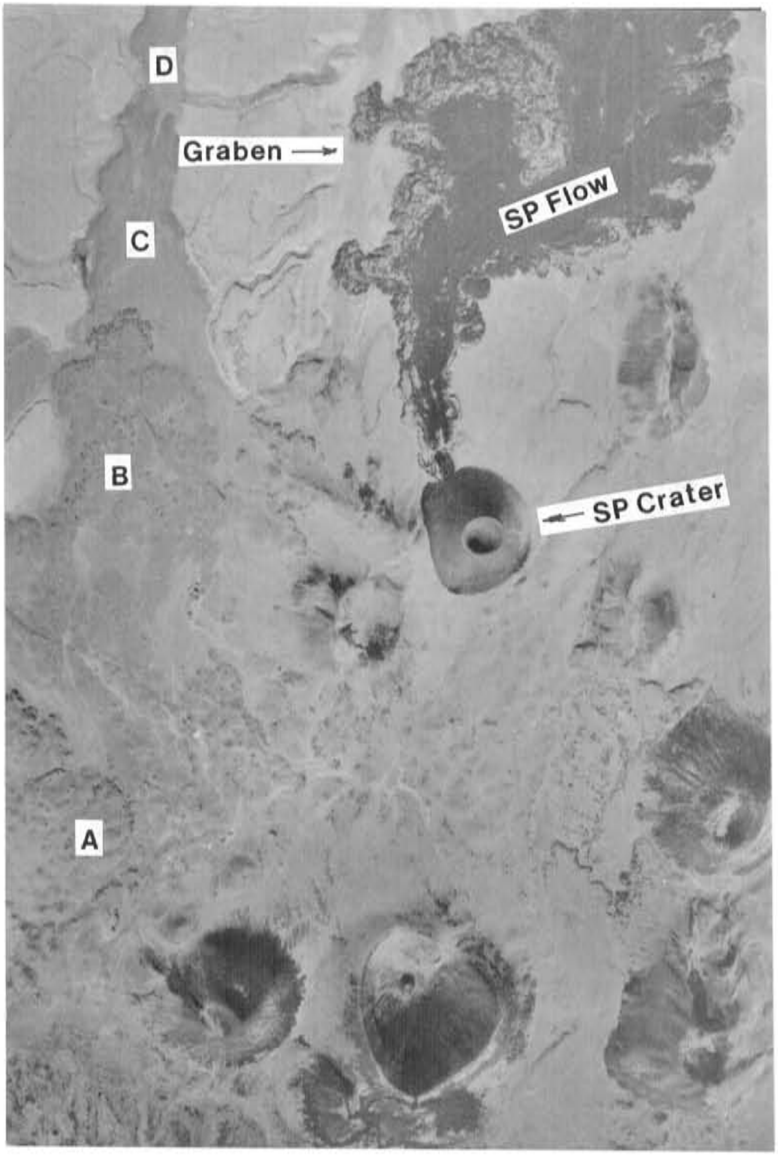

THE BLACK LAVA FLOW EXTENDING NORTHERLY FROM SP CRATER HAS BEEN DATED BY RADIOMETRIC METHODS AT ABOUT 71,000 YEARS. SEVERAL OTHER CRATERS IN THE PHOTOGRAPH ARE MUCH MORE DEGRADED INDICATING THEY ARE OLDER. THE SP FLOW EXTENDS ACROSS A GRABEN FAULT INDICATING THE FAULT IS OLDER THAN THE FLOW. OTHER OLDER FLOWS OVERLIE OTHER FLOWS; FOR EXAMPLE FLOW A OVERLIES FLOW B, B OVERLIES C, AND C OVERLIES D. SUCH SUPERPOSITION, IN CONJUNCTION WITH SURFACE MORPHOLOGY, HELPS ESTABLISH THE RELATIVE AGES OF FAULTS AND VOLCANIC FLOWS.

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FIGURE 5

TYPICAL VOLCANIC LAND FORMS, MESA BUTTE AREA

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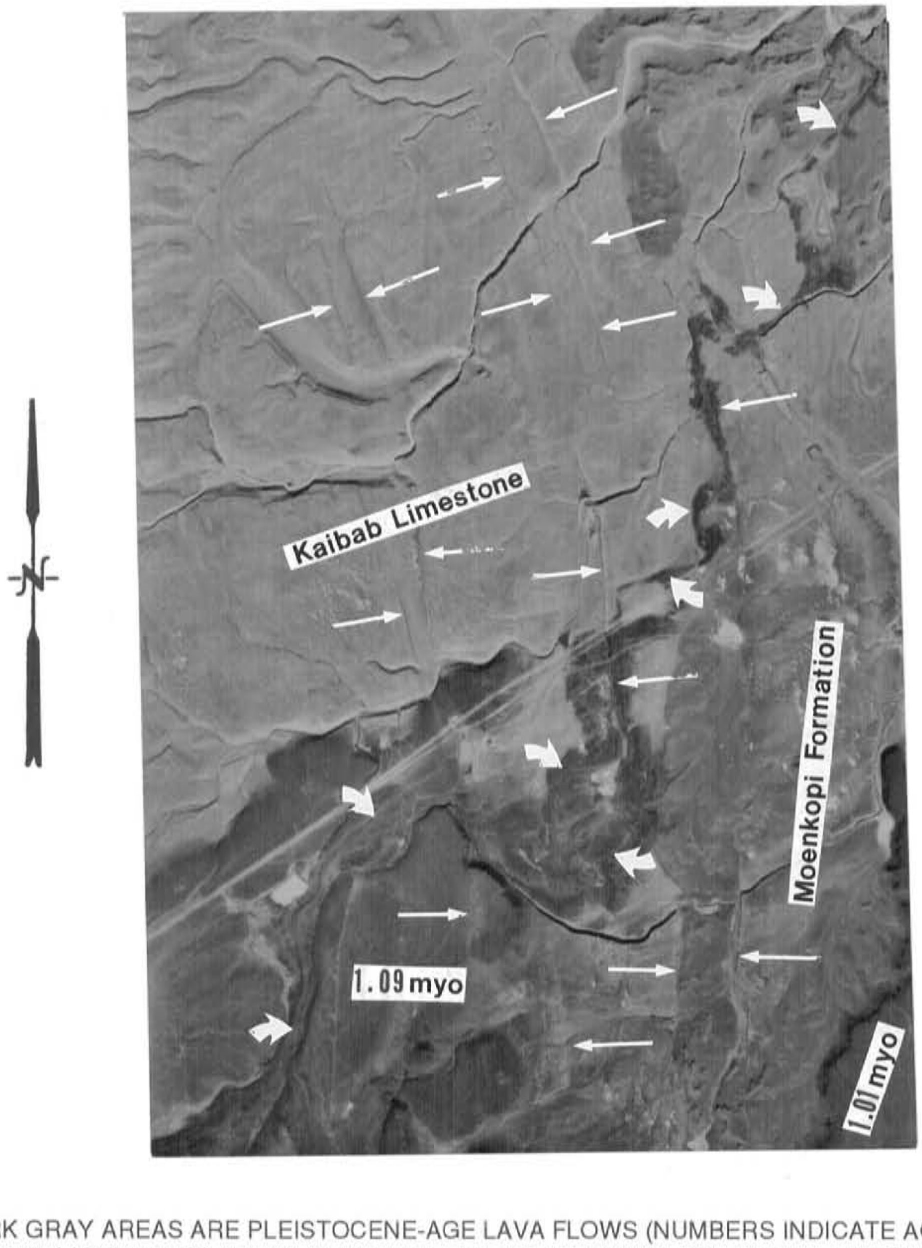

DARK GRAY AREAS ARE PLEISTOCENE-AGE LAVA FLOWS (NUMBERS INDICATE AGE IN MILLION YEARS); LIGHT GRAY AREAS IN UPPER LEFT ARE PERMIAN-AGE KAIBAB LIMESTONE; MEDIUM GRAY AREAS ON RIGHT ARE TRIASSIC-AGE MOENKOPI FORMATION. THIN WHITE ARROWS INDICATE FAULTS. LARGE WHITE ARROWS SHOW SERPENTINE TAPPAN WASH LAVA FLOW (530,000 YEARS OLD).

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FIGURE 6

AERIAL PHOTOGRAPH OF MESA BUTTE AREA

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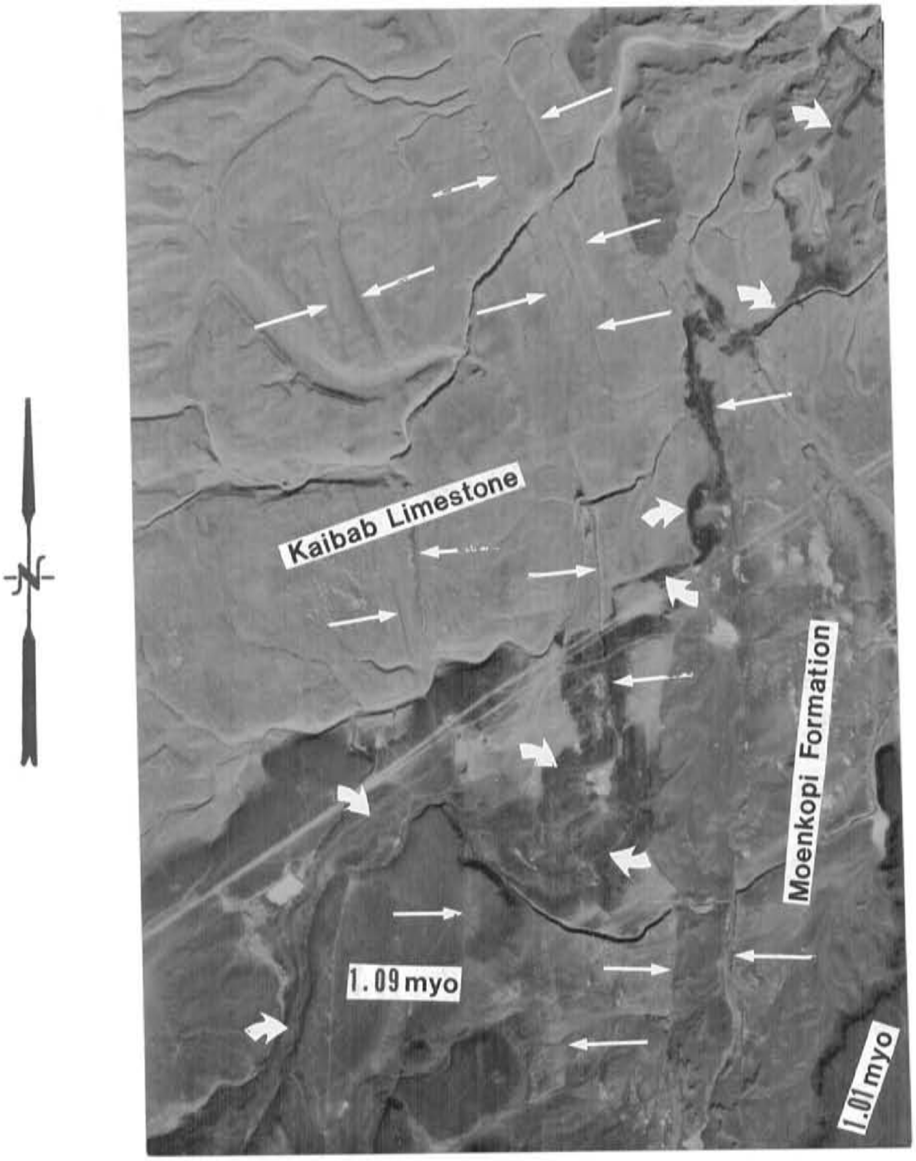

DARK GRAY AREAS ARE PLEISTOCENE-AGE LAVA FLOWS (NUMBERS INDICATE AGE IN MILLION YEARS); LIGHT GRAY AREAS IN UPPER LEFT ARE PERMIAN-AGE KAIBAB LIMESTONE; MEDIUM GRAY AREAS ON RIGHT ARE TRIASSIC-AGE MOENKOPI FORMATION. THIN WHITE ARROWS INDICATE FAULTS. LARGE WHITE ARROWS SHOW SERPENTINE TAPPAN WASH LAVA FLOW (530,000 YEARS OLD).

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FIGURE 6

AERIAL PHOTOGRAPH OF MESA BUTTE AREA

faulting for the Mesa Butte fault are:

- o The Mesa Butte fault was well developed before the Mesa Butte cones were formed and before Tappan Wash flow occurred (i.e. more than 500,000 years before present).

- o The Mesa Butte cinder cones do not appear to be offset by the Mesa Butte fault thus the fault in the cone area has not been active since the cones formed.

- o The southern part of the Mesa Butte fault is overlain by approximately 1 million-year-old lava flows that are not displaced by the Mesa Butte fault (although some smaller cross-faults do appear to displace these flows).

- o The Cedar Ranch fault merges with the Mesa Butte fault just north of the Mesa Butte cones, and was active after early Mesa Butte volcanic activity. The fault displaces the 530,000 year-old TW flow by a lesser amount than the 1.04 my-old Mesa Butte flow indicating recurrent displacements. The large amount of displacement of the Mesa Butte and TW flow by the Cedar Ranch fault suggests that the displacement occurred during several events. Several middle to late Pleistocene flows (estimated to be in the 200,000 to 300,000 age range) overlie the Cedar Ranch fault on the south indicating that the Cedar Ranch fault has not moved in late Quaternary time.

- Erosion has significantly deepened the Mesa Butte graben. Although the scarp is more than a thousand feet high in places, the true cumulative fault displacement generally is about 230 to 320 feet on the northwest fault, and net displacement across the graben is more like 100 to 200 feet. Assuming that surface displacements were large (say 10 feet per event) and that they were associated with earthquakes, the Mesa Butte fault could have generated about 10 to 20 large earthquakes. Of course, if the displacements were smaller, a larger number of events with smaller earthquakes would have been required to achieve the total cumulative displacement.

- None of the other faults which strike northwesterly across the Mesa Butte graben appear to significantly affect it, indicating that the Mesa Butte fault is one of the youngest, as well as the major fault in the area.

The Tappan Wash flow provides some of the most conclusive information regarding rate of faulting. The 530,000-year-old flow crosses about 18 fault zones. Eight of these fault zones do not offset the TW flow. Fault offsets occur at 10 locations yielding a minimum average activity rate of 1 event every 53,000 years if the scarps are a result of single-event ruptures. However, most of these events probably occurred over a period much shorter than 530,000 years. Based on lack of fault displacements in the latest Quaternary flows in the region, surface faulting does not appear to have been significant in the past 100,000-200,000 years so the 10 offsets probably occurred over a time span of no more than 300,000-400,000 years. This would make the average recurrence interval about 30,000-40,000 years. Furthermore, at some of the fault locations, the large cumulative offsets indicate that there were probably more than one offset and this would shorten the average recurrence interval even further. Without more detailed information, most of these age and recurrence estimates are gross calculations and conclusions are rather speculative. However, the lack of evidence for younger displacements of the TW flow would seem to suggest that the rate of faulting diminished in the latest Quaternary and has been considerably slower than during the middle Quaternary.

Some other general observations are:

- Surface faults were present as far back as latest Pliocene (about 2.5 million years ago).

- Most volcanism on the north side of the San Francisco volcanic field is in the 2 million to 200,000-year age-range (includes Sitgreaves, Kendrick, Humphreys, and O'Leary volcanos). More than 90 percent of the cinder cones are in the 700,000-to 100,000-year age range.

- Net cumulative displacements on all the faults are generally small, generally less than 100 feet.

- Many faults have multiple displacements.

- Based on the large number of faults displacing middle Pleistocene flows and the paucity of displacements in latest Quaternary flows, the time of greatest faulting activity appears to have been in the middle Pleistocene.

- There are more than 100 fault zones. If each of these faults had two displacements, there were would have been about 200 surface-rupture events since late Pliocene time. Assuming a time span of 3 million years, the average rate would be one event every 15,000 years. If that rate had continued until today, there should be about 17 faults in the area with evidence of late-Quaternary surface rupture. However, no such late Quaternary ruptures can be documented so the rate of faulting appears to have diminished considerably in latest Quaternary time (i.e. the past 100,000-200,000 years).

- The apparent age-range of the period of most faulting activity is the same as the time of most active volcanism. The volcanism appears to have been episodic, that is, rather than steady continuous activity, volcanism has been characterized by periods of high activity separated by long periods of quiescence. There is no indication of any significant changes in recent times so, just as more volcanic eruptions should be expected, so should more faulting and earthquakes.

- The above observations support Holm's (1987) assertion that one of the younger documented faults in the area is the Sinagua fault which he interpreted to be more than 250,000 years old.

- The only feature less than 100,000 years old in the Mesa Butte study area is the SP flow. There are several younger flows and cones in the eastern part of the San Francisco volcanic field such as at Sunset and Merriam craters but there are very few faults known in that area. Moore and Wolfe (1987) think that the apparent northwesterly alignment of some cones in the eastern area indicate buried northwest-trending faults.

- Historically, earthquakes have occurred in the area and some (1906, 1910), were in the 5.0 to 6.5 magnitude range (see Section 6. c. (11)). However, in the past few decades, this area does not appear to have been much more seismically active than the Arizona Mountain or Southwestern Plateau Margin zones.

In conclusion, the investigation in the Mesa Butte area indicates that surface faults with prominent scarps in the Paleozoic and Mesozoic rocks are probably neotectonic features. Some of these faults were active as far back as 1 to 2 million years, but many of them continued as active features into the late Quaternary time. However, the paucity of fault displacements in young flows indicates that the activity for the latest Quaternary (the past 200,000+) years is lower than it had been and, consequently, the surface-rupture hazard is also lower. The Mesa Butte fault system is one of the densest fault concentrations in Arizona. The faults occur in close proximity to young volcanism raising the question of whether the faults are a result of regional tectonic strain or whether they are due to local volcanotectonic activity resulting from crustal swelling and/or collapse over rising or evacuating subsurface magma chambers. The question reduces to whether the volcanism caused the faulting or whether the faults were already there and the volcanism opportunistically used the faults as access routes to the surface. The presence of similar faults throughout the Southwestern Colorado Plateau margin where there is little volcanism seems to favor the latter interpretation, and support the interpretation that the faults are indeed primary tectonic features related to regional tectonic forces rather than to just local volcanic processes..

(2) Verde Fault

The Verde fault is a northwest-striking basin-and-range-type normal fault that forms the boundary between the Black Hills (Mingus Mountain) block and Verde Valley on the northeast. Verde Valley is one of several normal-fault-bounded basins in the Arizona Mountain seismic source zone. These northwesterly trending valleys and their adjacent mountain blocks extend from southwestern New Mexico to the Hurricane and Toroweap faults in northwestern Arizona. The fault-bounded basins and ranges seen today began forming during the Miocene Basin and Range tectonic episode.

Their fault-bounded, tilt-block morphology is quite obvious, but they vary widely in degree of development and preservation. The Verde Valley fault system, along with the Big Chino Valley and Aubrey Valley systems, is one of the geomorphically more-youthful features suggesting that it has had a higher rate of tectonic activity in Quaternary time than the systems in the southeastern part of the zone such as the San Pedro and San Simon valleys.

Although there may have been some ancient activity along an ancestral Verde fault in both Precambrian and Laramide times (Lundberg, 1986; McKee and Anderson, 1971), Verde Valley appears to have formed primarily since about 10 million years ago based on the distribution and displacement of the Hickey basalts (10-14 million years old). The valley was well developed by 5.5 million years ago when the "Ramp Basalts" (5.5 to 8 million years old) flowed downslope into the valley from the area to the northeast.

Verde Valley had internal drainage until about 2 million years ago when lake beds of the Verde Formation and alluvial deposits filled the valley (Ranney, 1989). Presently, the valley drains southeasterly via the Verde River. With the development of through-flowing drainage, the Verde beds and the overlying alluvium have undergone extensive erosional downcutting and dissection. This downcutting, combined with continued localized deposition of alluvium in the valley has resulted in a complex assemblage of constructive and destructive landforms. Although these geomorphic surfaces provide a means by which to decipher the neotectonic development of the valley, they have not been investigated in detail. Such an investigation would be a major long-term undertaking and is well beyond the scope of the work for this investigation.

However, to assess the earthquake potential of the Verde fault, aerial photographs were analyzed and aerial reconnaissance and ground checking were performed. These investigations revealed that the Verde fault is a complex system of branching, discontinuous fault segments most of which appear to be within bedrock or at the bedrock-alluvium contact. There are at least two major segments and perhaps as many as four. For this investigation, the fault is considered to be composed of two segments, the northern and southern, similar to those designated by Menges and Pearthree (1983). The southern segment extends from the Tule Mesa area in the southeast to the Table Mountain area just northwest of Interstate 17 in the central part of Verde Valley. There does not appear to be a direct connection between the northern and southern segments. In the Table Mountain area, where the two segments overlap, the northern segment is about 2 miles west of the southern segment. The northern segment extends northwesterly, through the mining town of Jerome and into the hills at the northwestern end of Verde Valley. The total length of the fault could be as much as about 55 miles if northwestern and southeastern extensions beyond the valley are included. Considering only the segments of the fault that appear to have been involved in formation of the present Verde Valley, the northern segment would be about 20 miles long and the southern segment about 16 miles long.

The southern segment has the best evidence of late Quaternary displacement. For example, near the town of Camp Verde, a prominent, although short, scarp occurs in stabilized, alluvial-fan surfaces between Ryal Canyon and Allen Canyon. Herein, this scarp is referred to as the Allen Canyon Scarp. The age of these fan surfaces is uncertain but comparison of their morphology to other similar surfaces suggests great age, certainly several tens of thousands of years and probably more in the 10^5-year age range (see Section 3. d. (1)(c) for discussion of age estimation for fan surfaces). The surfaces are very flat and at first glance they might appear quite young. However, the degree of erosion in some areas indicates that these high-standing flat surfaces are just small remnants of a once-continuous valley-wide bajada. With the advent of through-flowing drainage in Quaternary time extensive downcutting occurred and new alluvial fans formed in the new washes creating a complex situation of nested fans that is difficult to interpret. There appear to be many potentially anomalous conditions with some local parts of the surface surviving much of the erosion. Overview of the valley shows several levels of younger surfaces inset into the higher surfaces supporting the interpretation that these higher surfaces must be quite old; possibly a few hundred thousand years old (200,000 to as much as 500,000). The fact that there is only one or two small fault scarps in such an old surface indicates very long recurrence intervals and very low slip rates for the Verde Fault. The prominent scarp in the high surface at Allen Canyon projects toward younger surfaces and alluvial fans, perhaps a few tens of thousands of years old, which have no apparent offsets. All of these factors suggest localized, minor reactivation of the Verde Valley fault rather than regular, continuous, large-magnitude offsets.

Field examination of the Allen Canyon scarp showed that the maximum height of this scarp in alluvial gravels is about 27 feet. The ground surface is covered with a well-packed, varnished pavement. The scarp crest is rounded and the maximum slope angles are about 15 to 19 degrees with the average being somewhat less. These relationships suggest the feature is of middle to late Pleistocene age. In one locality, the lower part of the scarp has a 28 degree slope. This steepened lower portion could represent a Holocene- to latest Pleistocene-age displacement of 6 to 7 feet but similar oversteepening was not observed anywhere else along the segment indicating that this short steep slope is a local erosional anomaly. The scarp is below a cluster of large boulders that armors the surface protecting it from erosion at that particular locality.

The fault responsible for the Allen Canyon Scarp is exposed in the steep walls of the unnamed wash north of Allen Canyon where it forms the contact between alluvial gravels and Miocene-age volcanic rocks. The fault zone is about 30 feet wide and strikes an average of about N 20° W and dips about 70 degrees northeast. A younger inset-terrace eroded into one of the walls does not appear to be offset by the fault.

In summary, the field data discussed above, like the aerial photograph interpretations, are inconclusive. Parts of the Verde fault scarp have similarities to scarps that formed within the past 10,000 to 20,000 years. However, there are several indications that the fault may be older, probably of middle or late Pleistocene age. Regardless of when the latest displacement occurred, the long-term average recurrence intervals between large surface-rupturing events appears to be long. Assuming that the 27-foot-high Allen Canyon scarp was formed by 6 to 9 foot displacements would indicate only 3 or 4 displacements since the high-standing alluvial surface formed. Using the ages of the fan surfaces indicated by the surface geomorphology, the average late-Quaternary recurrence interval would range from 50,000 to 170,000 years. Using the younger age and the maximum displacement yields a conservative slip rate of about 0.03 mm/yr. These numbers are similar to those determined for the Aubrey fault (Section 3.d.(2)).

The slip rates calculated from various other data such as total stratigraphic displacement, valley geomorphology, displacement of Miocene volcanics, fault-scarp morphology, and offset of Quaternary alluvial surfaces have a wide range. The maximum rate is about 0.2 mm/yr and the minimum is about 0.01 mm/yr.

The maximum credible earthquake was estimated by applying empirical fault-length/earthquake-magnitude relationships (Slemmons, 1982; Bonilla et al, 1984) and seismic-moment calculations (Hanks and Kanamori, 1979; Wyss, 1979). These calculations suggest the Verde fault is capable of generating earthquakes in the magnitude 7 + range. For the seismic hazard analysis a magnitude of 7.25 was estimated.

(3) Other Field Reconnaissance Areas

Reconnaissance visits were conducted in the Hualapai, Detrital, Sacramento, and Piute-Eldorado valleys of northwestern Arizona, southeastern California, and southern Nevada. These valleys and their adjacent ranges are unusually linear and relatively parallel for the Arizona area suggesting affinities to modern Basin-and-Range type faulting. The linear morphology, combined with the presence of a playa (Red Lake) in Hualapai Valley, suggests ongoing fault-controlled subsidence. Aerial photograph analysis, however, does not reveal any Quaternary faulting. Mountain-front tectonic geomorphic analysis indicates highly sinuous mountain fronts suggesting that the ranges have undergone extensive erosion without rejuvenation by tectonic uplift along mountain-front faults. In several northern localities, unfaulted Pliocene volcanic flows occur along valley margins in areas where surface faults would be expected if they had been active in Quaternary times. Rather than being a result of young tectonic activity, the strong linearity of the basins may be inherited from the previous tectonic regime, with enhancement by erosion during Quaternary integration of drainage to the Colorado River at the northern end of the valleys. This integration promotes erosion and provides direct egress of eroded sediments out of the valley thereby channeling the erosion and maintaining valley linearity. In summary, although there could be some ongoing late-stage tectonic subsidence, these basins and ranges do not appear to be very tectonically active so they were included with the Sonoran seismic source zone which is characterized by one of the lowest rates of tectonic activity in the state.

The southwestern margin of the Colorado Plateau is characterized by numerous long faults with prominent surface expression such as the West Kaibab (#3), DeMotte (#41), Muav (#47), and Moquitch (#40) faults (Plate 1). These faults are very obvious on aerial photographs (Figures 3 and 7) but some of the faults are in terrains covered with trees that obscure details. The area was checked by ground reconnaissance to see if any evidence of neotectonic faulting could be recognized. The DeMotte fault, for example, is expressed as a narrow linear graben up to 400 feet deep in places. Some of this depth may be due to dissolution of the carbonate bedrock in the graben. Evidence of dissolution in the form of sink holes is ubiquitous in the area. As is typical of faults in the southern plateau margin, net displacement is much less than the depth of the graben. Elevations on both sides of the graben are about the same indicating that faulting was primarily extensional with the central block downdropping between two normal faults. Although the bases of the fault scarps commonly had small Quaternary alluvial fans, no evidence of young faulting could be recognized. The morphology suggests that faulting was active in Quaternary time, as does comparison to similar faults in the Mesa Butte area, but fault displacements must be small, slip rates slow, and recurrence intervals long.

Field reconnaissance was conducted in several other areas during the project. Some areas were specifically targeted while others were visited during traverses between other areas. During the course of the project most of the state where neotectonic faults occur, and the margins of the surrounding states, were investigated by at least one of the investigatory methods (aerial photographs, ground reconnaissance, aerial reconnaissance). The only part of the state that didn't receive specific examination was the Sonoran Desert region. However, this area has been examined in detail several times by the project geologists, as well others, during several other projects during the past couple decades. The Research Team is quite confident that no major undiscovered surface faults exist in the area.

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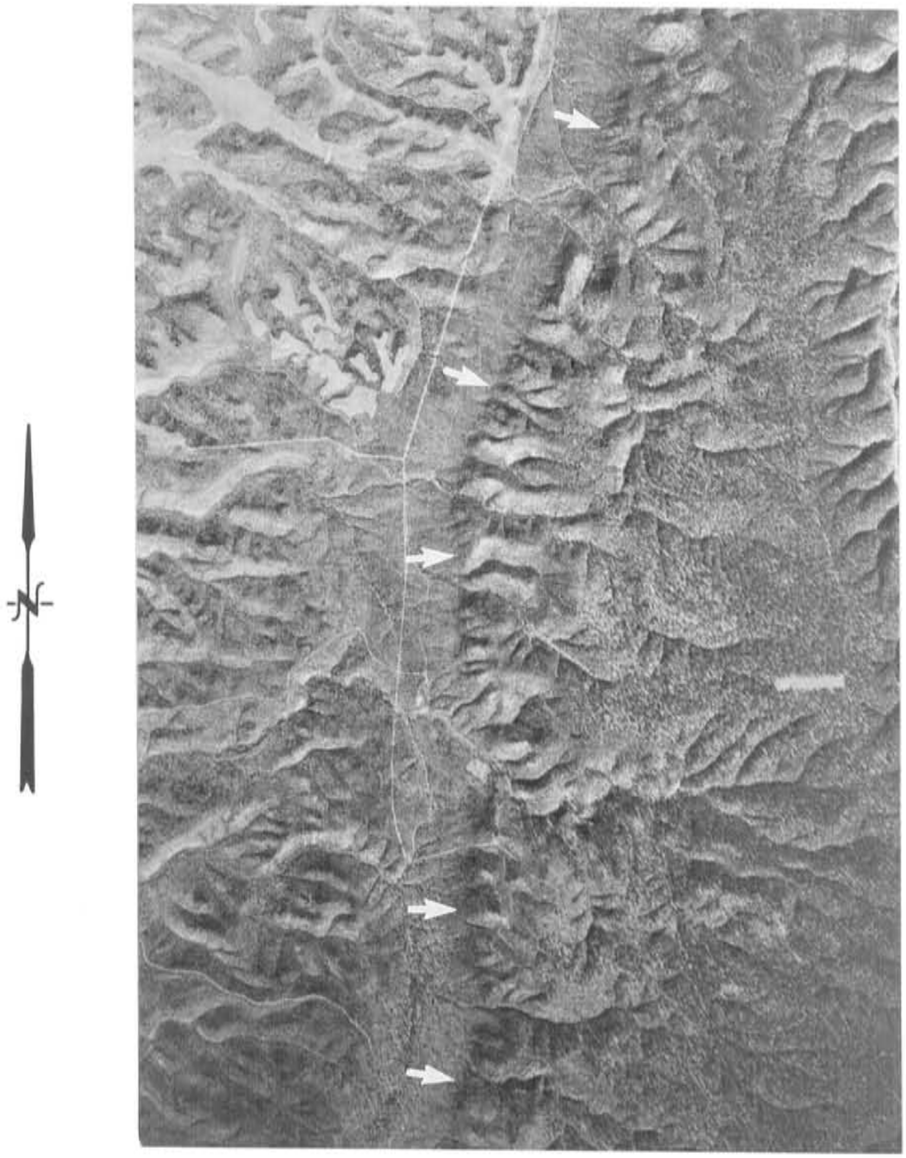

WHITE ARROWS SHOW LOCATION OF MAIN SCARP.

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FIGURE 7

AERIAL PHOTOGRAPH OF WEST KAIBAB FAULT #3

d. <u>Fault Trenching</u>

(1) **Big Chino Fault**

(a) **Background:** The Big Chino fault is an important fault for understanding the neotectonics of the north-central Arizona region. The fault is one of several northwest-striking faults in the transition zone (herein referred to as the Arizona Mountain Seismic Source Zone) between the Central Colorado Plateau and the Sonoran Desert (Plate 1). However, unlike some adjacent seismotectonic zones, the Arizona Mountain zone is both seismically active and has several young faults that have ruptured the ground surface in late-Quaternary time such as the Big Chino, Aubrey, Verde, and Horseshoe faults. Of these faults, the Big Chino fault appeared to be the one that ruptured last and had the best characteristics for evaluating recurrence intervals, faulting rates, and earthquake potential.

Three trenches were excavated across the main scarp in Big Chino Valley (Figure 8) to assess the earthquake potential of the Big Chino fault and to acquire details on the nature of faulting such as fault plane orientation, gross displacement, displacement per event, and age of displacements. Also, geologic and geomorphic analyses were conducted. These included terrace and alluvial-fan morphology evaluation, fault-scarp-morphology analysis, aerial-photograph analysis, and field checking of the fault at strategic locations along the surface trace on the ground.

Based on aerial reconnaissance, aerial-photograph interpretation, review of existing literature, and preliminary ground reconnaissance, an area on CV Ranch in the northern part of Big Chino Valley was selected for Trenching (Figure 8). Trenches were excavated on October 8 through 11, 1991. The fault is characterized by a prominent linear escarpment extending for a distance of about 35 miles. Figure 9 shows the typical surface expression of the Big Chino fault along the southwest flank of Big Black Mesa. The great length and apparent youthfulness of the fault make it a very important feature for evaluating the size and frequency of earthquakes, not only in the Chino Valley area but also for the entire transition zone area between the Colorado Plateau and the Sonoran Desert.

Three trenches were excavated across the trace of the Big Chino fault at an area known to local ranchers as Sheep Camp (Figure 10). The area was deemed to be especially well-suited for deciphering the faulting history because there are several well-developed terraces in the Quaternary alluvium (Figure 11). The occurrence of terraces at several different elevations indicates episodic changes in stream base level and commonly these changes are caused by uplift/subsidence due to vertical fault displacements. However, such terraces can also be the result of changes in stream capacity due to increase in stream flow such as might accompany changes in global climate, local cyclic weather trends, or catastrophic flooding events. At Sheep Camp there are about six levels of terraces that had been postulated to represent faulting events (Soule, 1978) and it was important to determine if they represented individual faulting events, and, if so, what was the frequency of faulting and how much displacement occurred per event. Soule's previous work (1978) was a university masters thesis primarily analyzing

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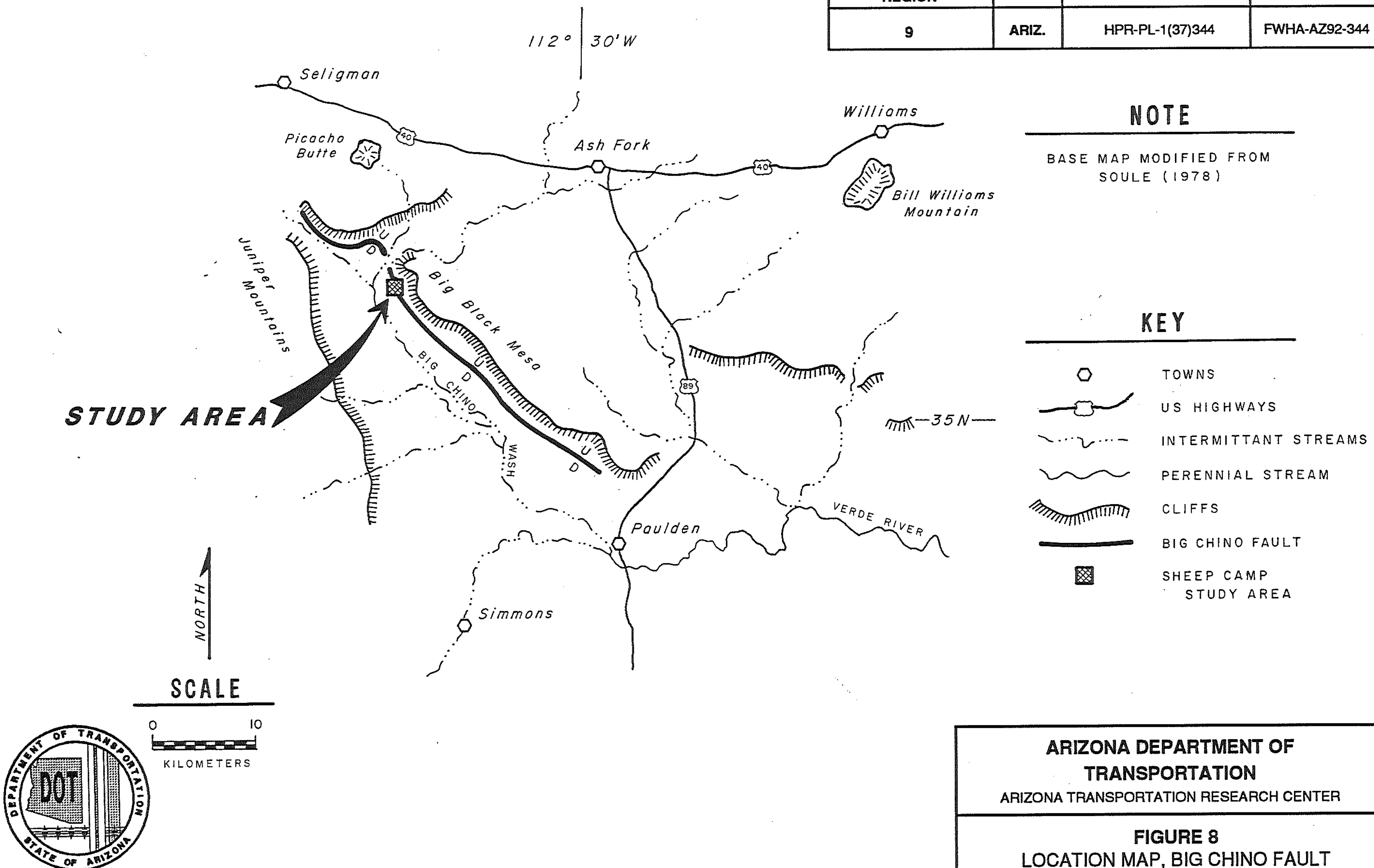

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FIGURE 8
LOCATION MAP, BIG CHINO FAULT

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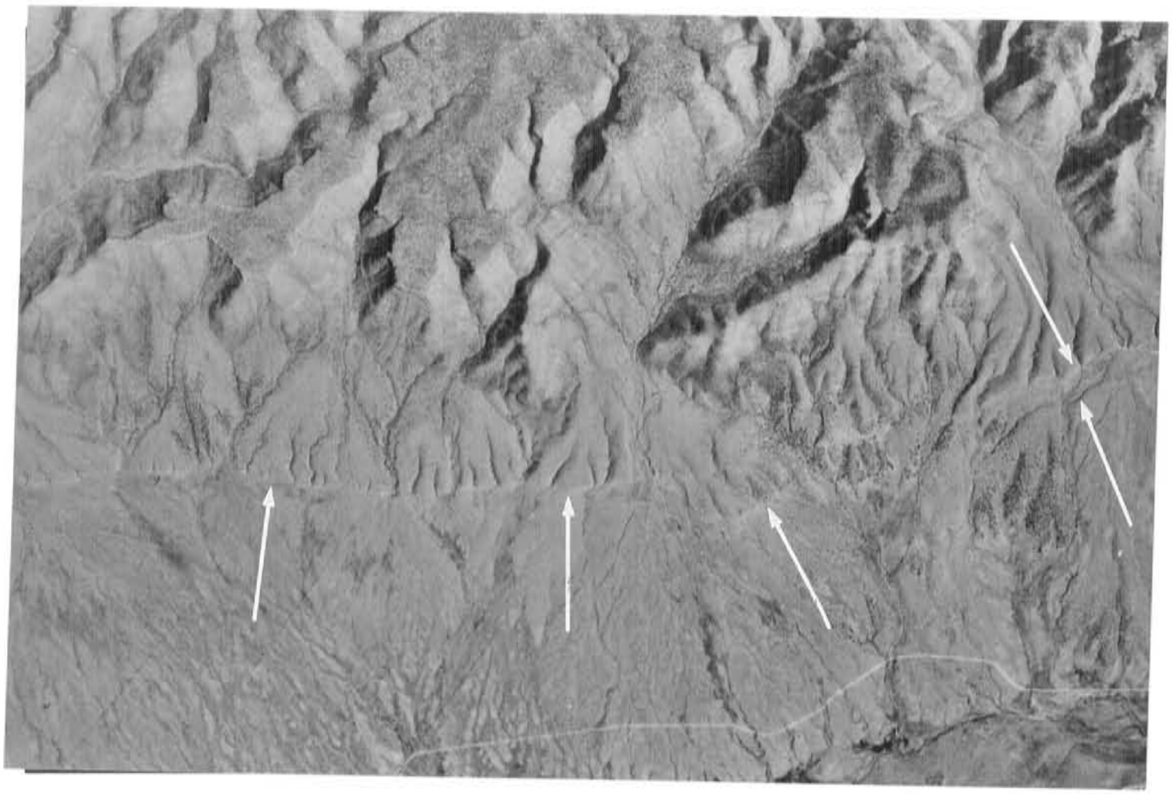

THE FAULT SCARP IS SHOWN BY THE ARROWS. THE AREA TO THE NORTHEAST HAS BEEN UPLIFTED ALONG THE FAULT RELATIVE TO VALLEY ON THE SOUTHWEST. THE MAXIMUM HEIGHT OF THE SCARP ALONG THIS SEGMENT OF THE FAULT AVERAGES ABOUT 80 FEET. ALSO NOTE ALLUVIAL GRABEN AT EXTREME RIGHT EDGE OF PHOTOGRAPH (INDICATED BY DOUBLE ARROWS). THE FAULT SEGMENT SHOWN ON THIS PHOTOGRAPH IS ABOUT 6 MILES LONG.

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FIGURE 9

AERIAL PHOTOGRAPH OF BIG CHINO FAULT
BLACK MESA SEGMENT, CHINO VALLEY, ARIZONA

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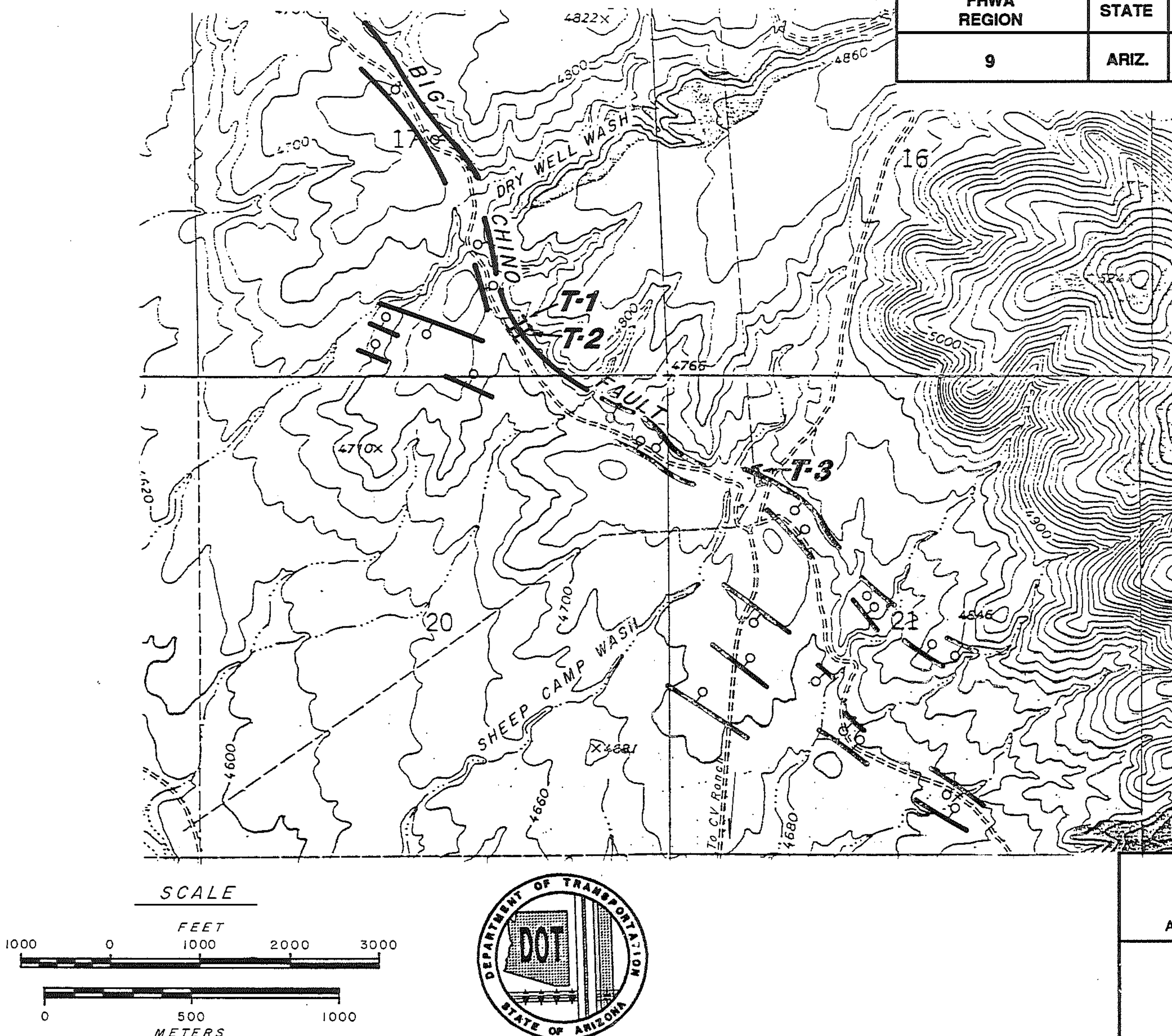

NOTE: BASE MAP ENLARGED FROM SOUTH BUTTE 7.5 MINUTE TOPOGRAPHIC QUADRANGLE (USGS, 1973)

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FIGURE 10
FAULT MAP, SHEEP CAMP AREA
BIG CHINO VALLEY
T20N, R4W, YAVAPAI COUNTY, ARIZONA

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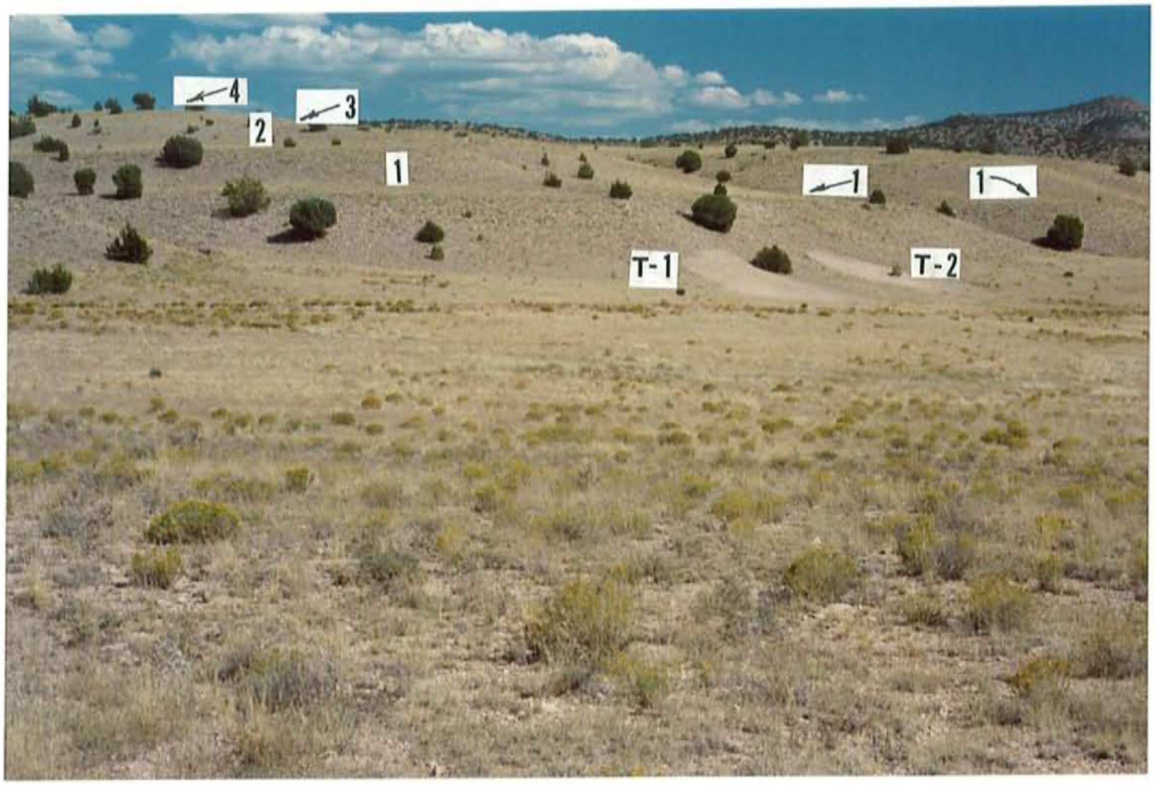

BIG CHINO FAULT IS ALONG THE BASE OF THE SLOPES. FOUR LEVELS OF TERRACES ARE SHOWN ON THIS PHOTOGRAPH. LEVEL 1 IS ABOUT 40 FEET HIGH. THE LIGHT, NON-VEGETATED AREAS ON THE RIGHT SIDE OF THE PHOTOGRAPH ARE THE LOCATIONS OF TRENCHES 1 AND 2. VIEW IS TOWARD THE EAST.

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FIGURE 11

TERRACES ALONG BIG CHINO FAULT
SHEEP CAMP STUDY AREA

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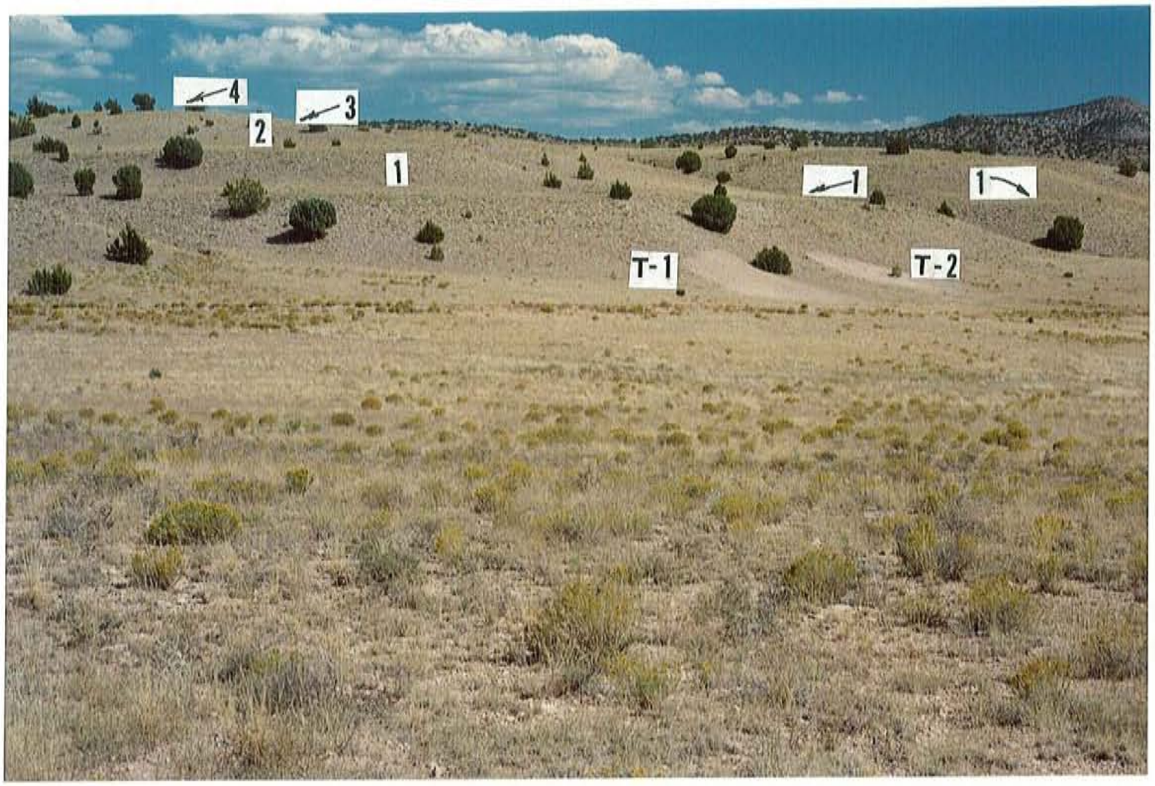

BIG CHINO FAULT IS ALONG THE BASE OF THE SLOPES. FOUR LEVELS OF TERRACES ARE SHOWN ON THIS PHOTOGRAPH. LEVEL 1 IS ABOUT 40 FEET HIGH. THE LIGHT, NON-VEGETATED AREAS ON THE RIGHT SIDE OF THE PHOTOGRAPH ARE THE LOCATIONS OF TRENCHES 1 AND 2. VIEW IS TOWARD THE EAST.

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FIGURE 11

TERRACES ALONG BIG CHINO FAULT
SHEEP CAMP STUDY AREA

surface geomorphology and soil-profile development. Our preliminary analysis indicated that only two or possibly three of the terraces occurred consistently elsewhere along the fault so it was questionable as to whether all of the terraces were tectonically controlled or whether some of them represented local fluvial effects of local creeks.

The three trenches were excavated at two sites which, based on geomorphology, seemed to represent the best locations for unambiguous results. In the selection of trench locations it is important to select sites that will reveal several layers of strata free from local or anomalous erosional or depositional events, and these layers must be shallow enough to be excavated by standard digging equipment such as a backhoe or a bulldozer. At one site, two trenches (T-1 and T-2) were excavated (Figures 10 and 11). Trench 1 was the principal trench. Trench 2 was a confirmatory trench, excavated to ensure that the relationships seen in T-1 were indeed typical and representative of the faulting/depositional regime. T-3 was excavated across a smaller scarp near a drainage referred to herein as Sheep Camp Wash (Figures 10 and 12). The depth of trench excavation depended on three factors: 1) the hardness of the material, i.e. the depth of refusal, 2) the deepest digging capability of the backhoe, or 3) the depths where stratigraphy was adequate to make reliable determinations. The maximum depth capability of the backhoe was about 14 to 15 feet. This depth was needed only in T-3.

The trenches were excavated across the faces of the main fault scarp. The scarp at T-1 and T-2 was about 40 feet high; at T-3 the scarp was about

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VIEW LOOKING NORTHWEST. TRENCH 3 WAS EXCAVATED ACROSS THE SCARP JUST THIS SIDE OF THE BARBED-WIRE FENCE. THE SCARP ON THE RIGHT IS ABOUT 15 FEET HIGH.

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FIGURE 12

BIG CHINO FAULT SCARP AT TRENCH 3 LOCALITY

15 feet high. Smaller scarps are sometimes better for trenching because correlative layers are more likely to be found on each side of the fault thereby allowing better estimates of amounts and timing of displacements. The length of the trenches were 40 feet (T-2), 66 feet (T-1), and 85 feet (T-3). Prior to logging, a level line was established on one wall of the trench for reference purposes. The trenches were logged by the project geologists at a scale of 1 inch to 5 feet (Figures 13 and 14) and 1 inch to 10 feet. Dr. Philip Pearthree (Arizona Geological Survey) visited the trench sites and provided helpful observations and insightful discussions with the project geologists. Dr. Pearthree also made a detailed soil-profile description in T-1 (Figure 13c). Upon completion of logging, the trenches were backfilled and the ground surface was restored to the original natural contour as much as possible.

(b) Trenches: Logs of trenches 1 and 3 are presented as Figures 13 and 14. The fault was clearly revealed in both trenches and appears as a zone of disruption in the otherwise layered alluvial sediments. Shearing was minimal in both trenches, as is typical for normal faults in alluvium. Only Trench 3 had a layer (soil Units 6 and 10) that could be correlated to both sides of the fault (Figure 14). This layer provided good information on the amount and age of faulting. Both trenches had well-developed dipping wedges of alluvium (Figure 13, Units 3-6; Figure 14, Units 2-4, 7, 5). Such wedges, commonly called colluvial wedges, represent detritus eroded from newly formed fault scarps and deposited at the base of the scarp. The number of wedges provides information on the number of surface-rupture events. Generally the bulk of these wedges is deposited

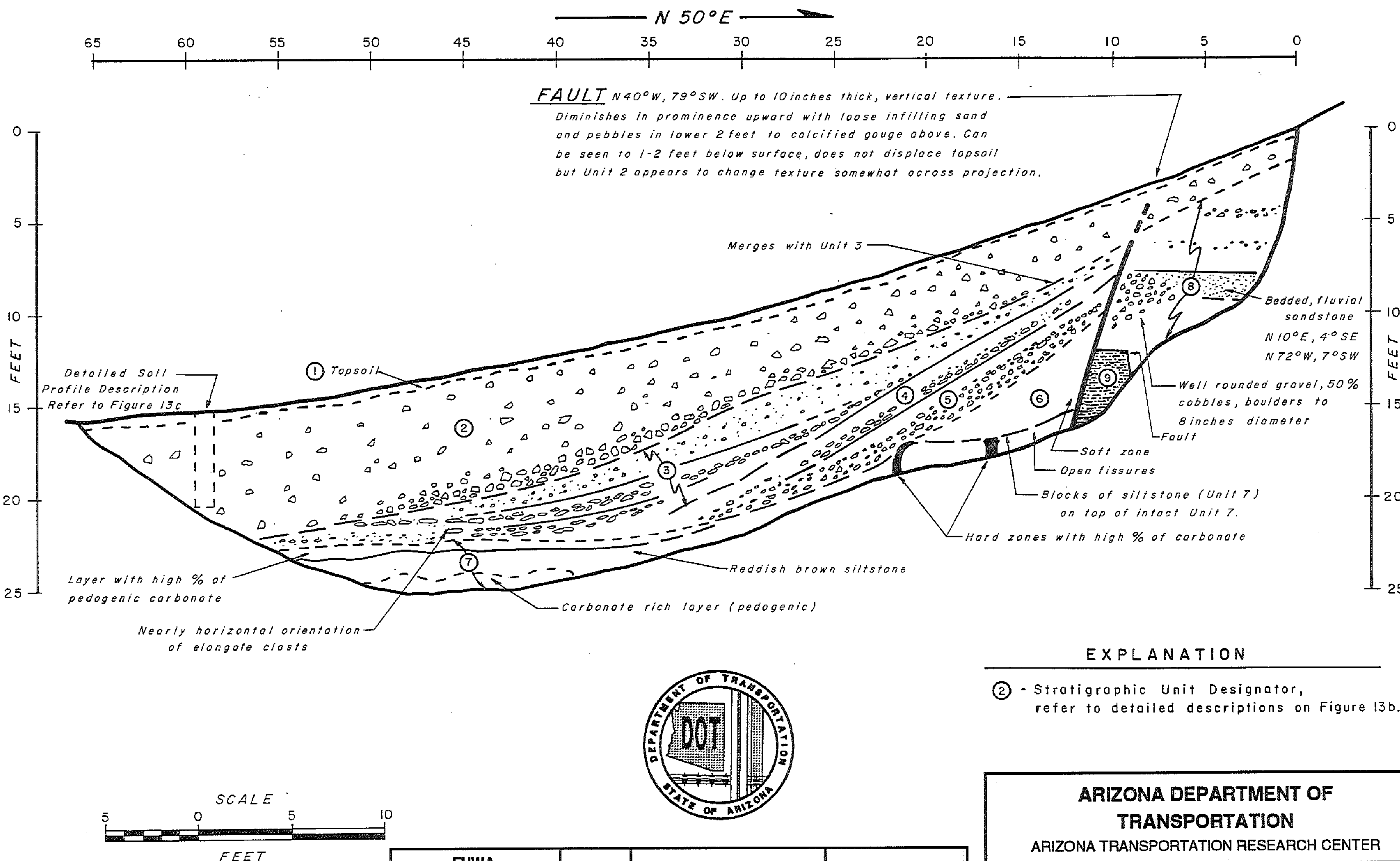

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FIGURE 13a

TRENCH NO. 1 - BIG CHINO FAULT

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Unit No. Description

1) TOPSOIL: Brown (7.5YR 5/2) to dark brown (7.5YR 3/4), gravelly loam, fine-coarse, subangular blocky structure, slightly hard to hard, wavy lower boundary. Thin carbonate coating on some pebbles (see Detailed Soil Description, Figure 13c).

2) GRAVELLY SAND: Pale brown (10YR 6/3), yellowish brown (10YR 5/4), and dark brown (7.5YR 5/4); some mottling. Gravel comprises about 30 percent to 50 percent of unit except for basal layer which is 80% subangular to subrounded pebbles and cobbles. Hard sandy clay matrix. Massive; basal layer is the only noticeable bedding. Clasts range from pebbles to cobbles of 4 - 6 inch diameter. Basal layer has slight imbrication; carbonate occurs as thin strings, lenses, and spots (Stage II); harder than upper part of unit due to better carbonate cementation. Moderately sharp, irregular lower contact (see Detailed Soil Description, Figure 13c).

3) SANDY GRAVEL: Brown to pale brown. Clasts generally in pebble to small cobble (2-inch diameter) size range. Rounded to subangular. Moderately hard to hard depending on carbonate cementation. Poorly bedded, some very slight imbrication of clasts in upper part of unit to moderately well imbricated and weak bedding in lower part of unit. Some discontinuous zones of pedogenic carbonate accumulation with completely coated clasts (Stage II). Gradual to diffuse, irregular lower contact.

4) GRAVELLY SAND/GRAVEL: White to very pale brown. Grades downward from gravelly sand to sandy pebble gravel to pebble-cobble gravel. Clasts in lower layer are generally in pebble to 2 - 3 inch size-range, but some rare cobbles are 6 to 8 inches. Strongly imbricated. Hard, cemented with pedogenic carbonate. Sandy upper part of unit is a completely plugged white carbonate zone; lower part of unit is a gravel with clasts completely coated with carbonate. Tops of clasts have thin films, undersides have irregular buildups to 2mm thick; where clasts are plucked out, a well-developed carbonate rind remains. Moderately sharp, wavy lower contact.

5) GRAVELLY SAND/GRAVEL: (Identical to Unit 5, Unit 4 and 5 could be beds within the same depositional unit).

6) SANDY GRAVEL: Gray to brown; overall color appears gray but zones of brown occur throughout; upper 1 to 1.5 feet is reddish brown. 30 - 40% gravel, 5% silt. Clasts range from pebble to cobble size, 10 - 15% of gravel is cobbles. Clasts are well rounded to subangular (5%), mostly volcanic rocks but some blocks of siltstone similar to Unit 9 are present. Most of these siltstone blocks and fragments are within the upper 1 - 2 feet. Friable, dense, slight cohesion. Poorly bedded, slight imbrication (7° apparent dip). Lower contact is sharp but wavy.

Upper reddish-brown zone appears to be soil developed on the gray gravel. Clasts in this upper zone have carbonate coating up to 1mm thick on undersides. Matrix has disseminated carbonate.

7) SILTSTONE: Reddish brown (7.5YR 4/6) to white. Scattered and pockets of angular to subrounded pebbles and small cobbles. Vesicular, 5% open root holes. Hard, dry. Both the top and bottom are calcic zones; the bottom calcic zone is completely plugged (Stage III).

8) GRAVEL: Grayish brown, brown to yellowish brown. Predominantly pebbles with small cobbles and few large cobbles with sandy matrix. Well rounded, loose to moderately loose. Poorly bedded but nearly horizontal fabric is obvious in several zones. Middle part of unit is well-bedded, moderately hard, dry, friable, sandstone.

9) SILTSTONE: Very pale brown to reddish brown, with scattered pebbles and beds of silty sand. Moderately well bedded with 2 to 4-inch-thick beds. Slightly moist. Moderately hard but can be disaggregated with difficulty by fingers. Violent reaction to HC1. Very jointed into angular fragments 1 to 2 inches wide. Joint surfaces have black spots and films. Beds near fault plane are bent indicating vertical drag.

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FIGURE 13b

TRENCH NO. 1 - BIG CHINO FAULT
SOIL DESCRIPTIONS

Horizon	Depth (In.)	Color	Structure	Consistency	Texture	Boundary	Carbonate
A	0 - 3	7.5YR 5/4 (dull brown)	Moderate Fine-med	Slightly hard	Gravelly loam	Wavy	Stage IC, Effervescent within discontinuous pebble coatings
		7.5YR 3/4 (dark brown)	Subangular	Slightly sticky Slightly plastic			
Bwk I	3 - 6.5	7.5YR 5/2 (grayish brown)	Moderate	Slightly hard-hard	Gravelly loam	Wavy	Stage IC, Effervescent, few thin discontinuous pebble coatings
		7.4YR 3/2 (brownish black)	Fine-Coarse sbk	Slightly sticky Slightly plastic			
Bwk 2	6.5 - 12.5	10YR 5/4 (dull yellowish brown)	Weak	Soft-slightly hard	Gravelly loam	Irregular	Stage I-II C, Strong effervescent, thin dis-continuous to nearly continuous pebble coatings
		10YR 3/4 (dark brown)	Fine-Med sbk	Slightly sticky Slightly plastic			
Bwk 3	12.5 - 24.5	10YR 6/3 (dull yellow orange)	Weak	Slightly hard-hard	Gravelly loam	Wavy	Stage II C, Violent effervescent, filaments & whitened matrix, soft discontinuous continuous pebble coatings
		10YR 4/3 (dull yellowish brown)	Fine-coarse sbk	Slightly sticky Slightly plastic			
Bwk 4	24.5 - 37.5	7.5YR 5/4 (dull brown)	Moderate	Hard	Very gravelly loam/clay loam	Irregular	Stage II C, Violent effervescent, whitened matrix, harder continuous, dis-continuous pebble coatings
		7.5YR 3/4 (dark brown)	Medium-coarse sbk	Slightly plastic Sticky			
Bk	37.5 - 61	7.5YR 6/4 (dull orange)	Massive	Soft	Gravelly sandy loam		Stage I, Strong effervescent, thin, discontinuous pebble coatings
		7.5YR 3/4 (dark brown)		Slightly sticky Slightly plastic	Loam		

Notes: Horizons

A - accumulation of humified organic material mixed with mineral fraction, the latter is dominant.
B - underlies A horizon, little or not evidence of original sediment structure.
Bw - color change or soil structure relative to C horizon, little evidence of clay or silt accumulation.
Bk - accumulation of calcium carbonate.
C - may have weathered material, but otherwise no soil development (parent material)

Abbreviations

sbk - subangular blocky
c - clear
irreg - irregular
sl - slightly
med - medium

Reference: Birkeland, P.W.; 1984.

Surface soil at base of scarp, southwest end of trench. Correlative with unfaulted unit in northeastern portion of trench, some colluvial input, but less than closesr to the scarp. (See Figure 13a) for profile location).

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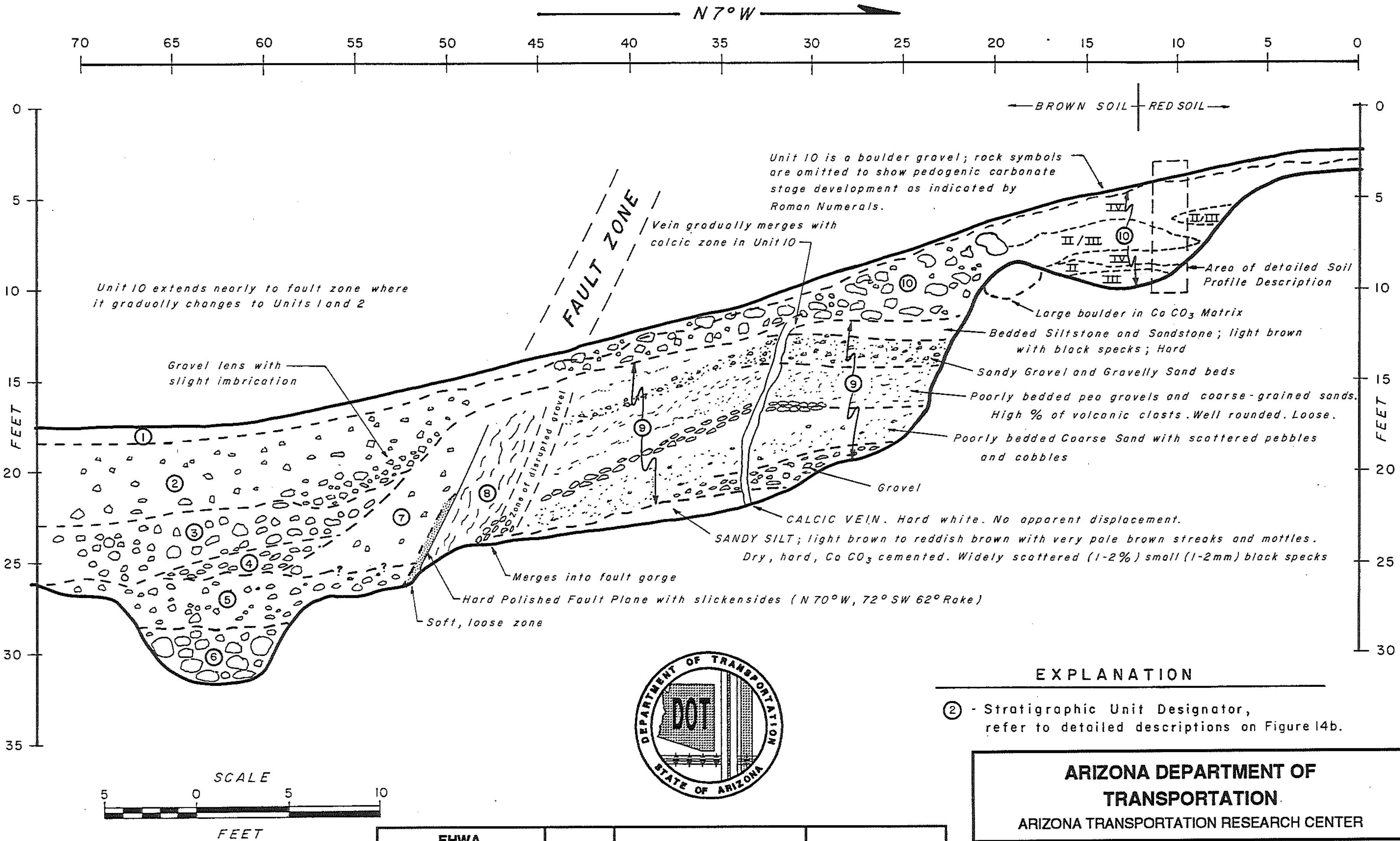
FIGURE 13c
TRENCH NO. 1 - BIG CHINO FAULT
SOIL PROFILES, UNITS 1 AND 2



EXPLANATION

② - Stratigraphic Unit Designator, refer to detailed descriptions on Figure 14b.

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FIGURE 14a
TRENCH NO. 3 - BIG CHINO FAULT

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Unit No. Description

1) TOPSOIL: Dark Brown (7.5YR 3/4), gravelly sandy loam, fine-medium blocky structure, dry, soft and crumbly. Abundant fine rootlets. Gradual-diffuse lower contact. Gravel content increases upslope and soil becomes thinner and less distinct on scarp face where it merges into unit 10.

2) SILTY SAND WITH GRAVEL: Brown to dark brown. (7.5YR 5/4-5/2), 5 to 10% pebbles and small cobbles, subrounded to subangular, size of clasts increases toward bottom of unit. Dry, hard to friable. Lower contact moderately sharp, clear and undulating.

3) BOULDER GRAVEL: Light brown to light gray. Well rounded to subrounded clasts with calcic coatings completely surrounding clasts. All clasts are sedimentary rocks, predominantly limestone but some sandstone and quartzites also are present. Calcic coatings are thin films (< 1mm). Unit appears similar to Unit 2 but is coarser grained and has more advanced carbonate development (Stage II). Lower contact undulating but moderately sharp.

4) GRAVEL: White, hard, dry, tightly cemented with $CaCO^3$. Poorly sorted from granules to boulders in sandy matrix. Small cobbles are most abundant. Well rounded to subrounded clasts of sedimentary rocks clasts are completely coated with calcic rinds, a few rinds appear thicker on top of clast suggesting reworking of older K horizon; calcic nodules up to 1 inch diameter are common in matrix (Stage II-III). Some imbrication of clasts. Lower contact moderately sharp.

5) SILTY SAND AND GRAVELLY SILT: Multicolored; yellowish red (5YR 5/6), pale brown (10YR 6/3), and white. Pebbles and cobbles are widely disseminated to lenticular. Some fine grained areas are white due to high carbonate content. Slightly moist, moderately hard. Vesicular, some vesicles are open, some with calcic lining. Lower contact diffuse.

6) BOULDER GRAVEL: White to pale brown. Poorly sorted clasts of sedimentary rocks, mostly limestone, well rounded to subrounded. Poorly defined bedding, lenticular. All clasts coated with thin (< 1mm) to thick (5mm) calcic rinds (Stage III). Loose to tightly cemented.

7) SANDY SILT WITH GRAVEL: White to very pale brown. Dry, hard, cemented with $CaCO^3$ (Stage IV). Slight imbrication of pebbles and small cobbles.

8) SILT AND SAND WITH GRAVEL: Cemented fault gouge. White to light brown. Dry, hard cemented with $CaCO^3$. Numerous shears, streaks, cracks, carbonate veins and strongly developed fabric with apparent dip of about 70-75 degrees. Southerly contact is abrupt in lower part with striated, polished surface (N 70° W, 72° W; slickensides 62° rake). Northerly contact moderately sharp.

9) SAND, GRAVEL, SANDSTONE, AND SILTSTONE: Gray to light brown. Well-bedded sequence with large percentage of volcanic clasts. Gray color derives from volcanics. Grain sizes comprise silt/clay to small cobbles but these are generally sorted into distinct beds within sub units, 1/2 cm to 2 cm size is most common. Some cross-bedding. Dry, loose to dense, spotty cementation. Disseminated carbonate, no significant calcic coatings. Bedding less defined south of calcic fissure vein.

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FIGURE 14b

TRENCH NO. 3 - BIG CHINO FAULT

SOIL DESCRIPTIONS

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10) BOULDER GRAVEL: White with red soil. Dry, hard, with loose zones. Poorly sorted with short discontinuous beds and lenses. Clasts to 1 meter diameter but 30 to 50 cm size is most common, well rounded to subrounded, thick calcic coatings and tightly cemented to loose. Clasts are all sedimentary rocks, mostly limestone with few sandstones. Trench log shows irregular distribution of carbonate development (see detailed soil profile description).

DETAILED SOIL PROFILE DESCRIPTION

Depth (Cm)	Horizon	
0 - 6	A	Strong brown (7.5YR 4/6) when dry; dark brown (7.5YR 3/4) when moist. Loam. Fine to medium granular; soft when dry, friable and slightly sticky when moist. Lower boundary diffuse.
6 - 20	B	Red (2.5YR 4/6) when dry; dark red (2.5YR 3/6) when moist. Silty clay loam with very fine-grained sand. Fine blocky and medium granular. Soft when dry, firm and slightly sticky when moist, slightly plastic when wet. Lower boundary gradual to diffuse. Developed in boulder gravel; pockets of soil extend around and under clasts.
20 - 95	K	White to very pale brown boulder gravel with lenses and layers of sandy pebble gravel. Strongest CaC0^{3} development is from 20 to 75 cm depth. This stage IV calcic horizon is completely plugged with discontinuous laminae in finer grained layers. These laminae can be broken down by finger pressure with difficulty and can be disaggregated completely with persistent effort. All clasts are completely coated with calcic rinds, maximum thickness on tops of clasts is about 1/2 cm. Rinds on bottoms commonly 1 cm and up to 3 cm where voids occur.
95 - 107		Carbonate development from 95 cm to 107 cm is variable from Stage IV to II depending on grain size and permeability/porosity. In areas below large boulders or impermeable laminae, carbonate development is early Stage II with calcic rinds less than 1 mm thick only on bottom of clasts.
102 - 203		Stage IV zone on west side of trench with laminar horizons and calcic rinds of 0.5 to 1 cm on some clasts. Laminae are discontinuous.

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FIGURE 14b (cont'd.)

TRENCH NO. 3 - BIG CHINO FAULT

SOIL DESCRIPTIONS

within a few hundred to a thousand or so years after the faulting event, until the scarp is worn back to the angle of repose (about 35 degrees) (see Section 6.a (3)). After that, further deposition is very slow and soils develop on the surface of the wedges until the next rupture occurs when a new scarp is formed and new colluvium is washed over the previous wedge and its soil. The length of time between successive faulting events is important for the development and recognition of these wedges. Faults with long times between surface ruptures will have colluvial wedges with well-developed soils and distinct contacts that can be more-easily differentiated than wedges along faults with short recurrence intervals, where the wedges tend to grade into one another.

It is interesting to note that in Trench 1, the deposits on the northeast side of the fault are not alluvial-fan deposits as was expected. Rather, these deposits were relatively well bedded, nearly horizontal, stream deposits typical of more low-energy, central-valley, depositional processes. Ground checking in the nearby canyons showed similar deposits underlying the entire area indicating these fine-grained deposits are quite extensive and not just a local fault sliver. These deposits indicate that Big Chino Valley had a long quiescent period without substantial surface faulting. Geomorphic analyses of alluvial surfaces in other parts of the valley indicate a long period of erosion and downcutting after the quiescent period, suggesting that the quiescence period probably existed during the early Quaternary, several hundred thousand years to more than a million years ago. The deposit is important because it indicates an episodic nature to the extensional faulting regime. However, such episodic tectonism is not unusual in the Basin and

Range province. The project geologist, as well as others, have documented several cases of similar long-term quiescence in the tectonically more-active central Basin and Range area of Nevada and Utah (Schell, 1982; Schell et al, 1981; Muir et al, 1981; Wallace, 1987; Ryall, 1977).

Soil-profile analysis at Trench 1 revealed that stratigraphic Unit 2 (Figure 13a) which overlies the fault and is unfaulted has moderate reddening, clay alteration, and carbonate accumulations indicative of soil formation since early Holocene to latest Pleistocene time, perhaps in the 8,000 to 10,000 year range. This age is supported by the presence of a small entrenched, but unfaulted, alluvial fan at the mouth of the stream channel just northwest of the trench which overlaps Unit 2 and has a surface geomorphology also indicating an early Holocene age. These data indicate that the latest surface rupture of the Big Chino fault occurred prior to Holocene time. A unit similar to Unit 2 overlies the fault in Trenches 2 and 3 (Figure 14). Although we deduce from this that the latest rupture was pre Holocene, it is uncertain as to how long before Holocene it might have occurred. The soils developed on the colluvial wedges indicate that the time between rupture events was quite long, on the order of at least several thousand years and most likely a few tens of thousands of years. In Trench 1 (Figure 13), the colluvial wedges (stratigraphic Units 3, 4, 5, and 6) all have substantial soil development in the form of reddened B horizons and (or) pedogenic carbonate accumulations typical of soils that have been forming for more than 10,000 years, to as much as several tens of thousands of years.

(c) Tectonic Geomorphology: Although the trenching across the Big Chino fault was successful in documenting several displacements and in quantifying typical amounts of displacements during faulting, the analysis suffers from lack of absolute age control. There are no dated alluvial materials in the Chino Valley area and we uncovered no material that could be dated. However, some general estimates of age and age ranges were estimated by analysis of geomorphic relationships and soil-profile development on alluvial fans and terraces.

Based on comparison of surface geomorphology to alluvial units in other parts of the Basin and Range using the tectonic geomorphology methods such as described by Christenson and Purcell (1985), Schell et al (1981), Muir et al, (1981), Schell and Muir (1982), as well as comparison to other dating studies such as in southern Nevada and New Mexico (Gile et al, 1981; Gile, 1986; Sowers et al, 1988), alluvial surfaces were categorized into order-of-magnitude age categories (e.g. 10^3, 10^4, 10^5, 10^6 years). For example, surfaces which once were flat, coalesced alluvial aprons but which now are dissected such that there are no flat surfaces between stream channels, which have had the soils stripped away by erosion, and which have complex dendritic drainage patterns can be several hundred thousand (10^5) to more than a million years (10^6) old. The erosion generally occurs at a rate dictated by climatic influences but uplift due to faulting can also increase the rate of surface dissection. Highly dissected surfaces with narrow flat areas between channels, wide flat washes, commonly with strong soil carbonate development, advanced soil formation, and closely packed interlocking surface pavements of pebbles and cobbles are typically a few to several hundred thousand years old (10^5). The degree of development of each of these characteristics narrows the age range within each order-of-magnitude category. For example, the highest alluvial-fan surfaces on the northeast side of Chino Valley fit into the 10^5 category but appear to be of the younger variety between about 200,000 to 400,000 years old. This surface has many similarities to the Jornada I surface in New Mexico that is about 250,000 to 400,000 years old (Gile, 1986). The same type of comparative analyses were used on the other surfaces throughout the entire valley and when the whole system is pieced together, a crude history of alluviation, uplift, and downcutting, presumably related to both climatic and tectonic effects can be deciphered for Big Chino Valley. Although the estimates have large uncertainties, the results do provide some useful age constraints for evaluating the rates of fault displacement and earthquake potential.

(d) **Fault Displacements:** The best data for determining the amount and age of displacement comes from Trench 3 where, unlike T-1 and T-2, an offset stratigraphic unit with measurable offset on one side of the trench could be matched to its offset counterpart on the other side of the fault. Based on lithologic characteristics and soil development, stratigraphic unit 6 appears to be the downfaulted equivalent of Unit 10 on the upslope side of the fault (Figure 14). This unit, which is about 80,000 to 100,000 years old based on soil-profile (Stage III-IV Calcic horizon) and surface-pavement development is displaced about 25.5 feet. The colluvial wedges in the trench (Units 2, 3, 4, and 7) suggest two or three subsequent displacements. Averaging these displacements over the estimated time span of 80,000 to 100,000 years indicates that the time between events was in the

20,000 to 30,000 year range and that displacements were about 6 to 9 feet per event. The 6- to 9-foot displacement are reasonable figures based on typical Basin-and-Range tectonics and local geomorphology. The thickness and configuration of Unit 5 suggest that prior to its deposition, the scarp was at least 5 feet high which would indicate a minimum offset of about that much.

The total cumulative displacement of the Big Chino fault, based on displacement of the highest-elevation alluvial-fan surfaces, can also provide information on amounts of rupture. Measuring scarp profiles from topographic maps indicates that the average height of the Big Chino Scarp is about 80 feet. Assuming this represents a total displacement of about 80 feet within late Pleistocene time (approximately the past 200,000 years) suggests surface ruptures of about 6 to 11 feet per event. However, these displacements are gross displacements along only the main fault and, as described above, most of the Big Chino fault is paralleled by a subsidiary antithetic (back-dipping) fault. For earthquake magnitude assessments, the net slip should be used and this requires that the slip on the subsidiary back-dipping fault be subtracted from that of the main fault. The back-dipping fault was not trenched but, based on geomorphology of the scarp, its total displacement appears to be about 25 percent of the main scarp, a value typical of Basin-and-Range type normal faults. Subtracting 25 percent of the displacement yields net displacements of about 4.5 to 8 feet per event. None of these estimates of displacement can be completely accepted at face value but they cluster around 4 or 5 to 9 feet which is typical of basin and range faulting and could very well represent the range of displacements during the prehistoric rupture events on the Big Chino fault.

In Trench 1, stratigraphic units could not be correlated across the fault because the displacements were greater than the depth of the trench. However, the number of colluvial wedges and their soil-profile development suggest 4 or 5 ruptures with similar recurrence intervals in the 20,000- to 30,000-year range.

Surface geomorphology indicates that the Big Chino fault is a normal fault dipping to the southwest with the valley side of the fault displaced downward relative to the mountain side. The trenches revealed a fault-plane dipping 60 to 70 degrees to the southwest (Figures 13 and 14). The surface geomorphology indicates only dip slip but Trench 3 revealed a polished shear surface with well-developed slickensides indicating a right-lateral component of slip of about 30-percent (Figure 15). In other words, as the southwestern or valley fault-block is displaced downward, it moves slightly to the left relative to the rocks on the other side of the fault which are displaced upward and to the right. Although such lateral-slip components are not uncommon in Basin and Range normal faults, just one occurrence of such a slip surface does not provide conclusive evidence that the entire fault has the same sense of slip over its entire length during every event because local geometric variations in fault strike can give apparent lateral components that do not represent the net regional slip.

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BETWEEN STATIONS 50-55 ON TRENCH LOG, TRENCH NO. 3. NOTE GROOVES AND STRIATIONS (SLICKENSIDES) ON SMOOTH POLISHED FAULT-PLANE SURFACE. ARROWS SHOW 60 DEGREE, OBLIQUE ORIENTATION OF SLICKENSIDES. GSA CARD SHOWS SCALE IN INCHES AND CENTIMETERS.

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FIGURE 15

FAULT PLANE OF BIG CHINO FAULT
TRENCH NO. 3

(e) Earthquake Potential: The size of earthquake that probably accompanied the displacements on the Big Chino fault can be estimated by comparison to historical earthquakes on similar faults in similar tectonic environments using fault length and displacements. Analysis of the geomorphology of Big Chino Valley revealed nearly continuous fault scarps along the northeast side of the valley in proximity to the mountain fronts of Big Black Mesa and Picacho Butte. The total length of these fault scarps is about 35 miles. The fault scarps appear to branch out in the Partridge Creek area with one splay extending straight northwesterly and dying out after about 5 miles in older, central-valley, alluvial deposits (Plate 1). The other splay strikes northerly a short distance along Partridge Creek to the mountain front near Picacho Butte then strikes northwesterly to the north end of the valley. On the north, the Big Chino Fault merges with or is transected by east-west trending faults in late Miocene-Pliocene volcanic rocks of the Mount Floyd volcanic field. On the south, the fault gradually dies out near Highway 89, or it may extend into the Paulden volcanics east of the highway.

Subtle differences in the geomorphology between the Big Black Mesa segment and the Picacho Butte segment suggest that the most recent displacement may have been confined to the Big Black Mesa segment from north of Highway 89 to the Partridge Creek area, a distance of about 18 miles (25-30 km). These differences include well-developed, higher, somewhat more distinct scarps and two well developed terrace levels on the Big Black Mesa segment.

(2) Aubrey Fault

(a) Background: The Aubrey study area was located in southern Aubrey Valley (Figure 16). The Aubrey fault is located between the Toroweap and Big Chino faults (Plate 1) in northwestern Arizona and is an important feature for understanding the relationship between the northeasterly striking faults of the Hurricane-Wasatch zone and the northwesterly striking faults of the Arizona Mountain zone. The prominent escarpment of Aubrey Cliffs is a conspicuous landmark along old U.S. Route 66 and had long been suspected of owing its bold cliff face and striking linearity to fault displacement. For example, the Geologic Map of Coconino County (Moore et al, 1960) shows a dotted line, presumably representing a buried fault, in about the same location as the fault shown on Plate 1. Menges and Pearthree (1983) were among the first to actually document the feature as a Quaternary fault. They showed the fault as comprising three segments along the base of the Aubrey Cliffs with a subparallel fault called the Aubrey Valley fault a short distance to the west of the main scarp. Menges and Pearthree assigned an age of Holocene-latest Pleistocene for the latest displacement along the southern part of the fault. To the north, the Aubrey fault merges with several fault splays extending south-southeasterly from the southern Toroweap fault system (Plate 1).

Aubrey Valley has the characteristics of a typical Basin-and-Range-type valley. These characteristics include an asymmetric profile with a gently sloping ramp descending easterly from the southern end of the Hurricane fault escarpment in the Peach Springs Canyon area to the Aubrey Cliffs. Sediments

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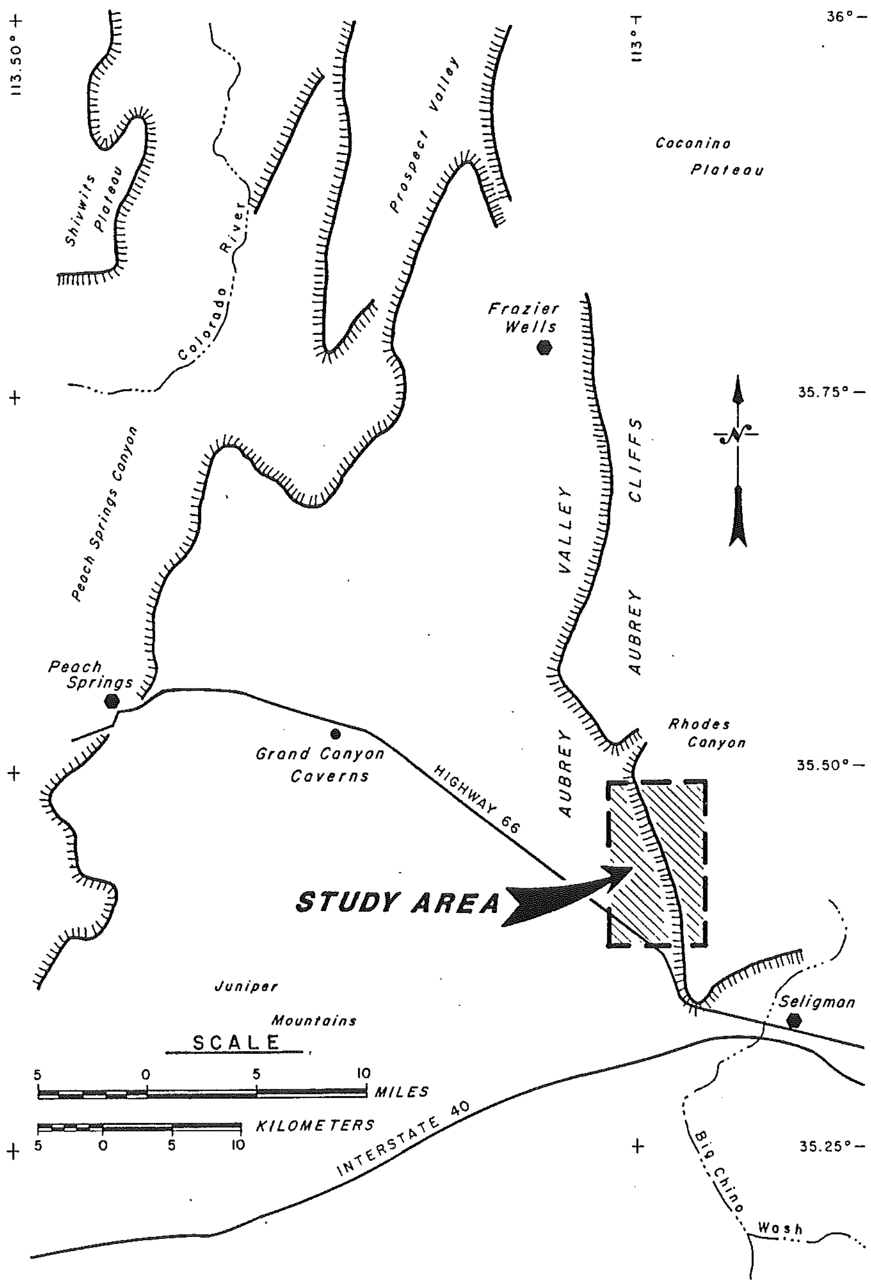

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FIGURE 16

LOCATION MAP - AUBREY VALLEY

eroded from the surrounding mountains have been washed into valley where they are trapped as alluvial valley fill because the valley is an enclosed basin without external drainage. The southern valley is the lowest part of the valley with a sill depth of about 5200 feet elevation. This lower part of Aubrey Valley was the site of a small lake during the late Pleistocene. Remnants of shoreline sand bars can still be recognized on aerial photographs. Based on the degree preservation of these features, the vestiges of this lake appears to have existed until just a few thousand years ago, similar to the glacial (pluvial) lakes in the Basin and Range province of Nevada, Utah, and California. These lakes reached their maximum development in the Basin and Range province about 12,000 to 15,000 years ago. Since that time most of them have dried up because of changing climate. Other subtle escarpments and lake-type deposits in Aubrey Valley extend northwesterly from the southern lake shorelines as shown on Figure 17. Fine-grained deposits in the low areas west of the more-northerly scarps suggest that at one time a smaller lake or catchment area probably existed in this area also. The presence of this lake and the enclosed basin indicate that Aubrey Valley is tectonically subsiding in response to crustal extension and downfaulting along the Aubrey fault at a rate faster than the erosional/depositional rates.

(b) Tectonic Geomorphology: Like most tilt-block Basin-and-Range-type fault valleys, Aubrey Valley has a major fault on one side of the valley (the Aubrey fault - #9 on Plate 1) and several minor faults on the other side (Blue Mountain fault #86; Pica Graben #13; Yampai Graben #14; Audley fault, #15 - see Plate 1). The Aubrey fault, like many of the faults

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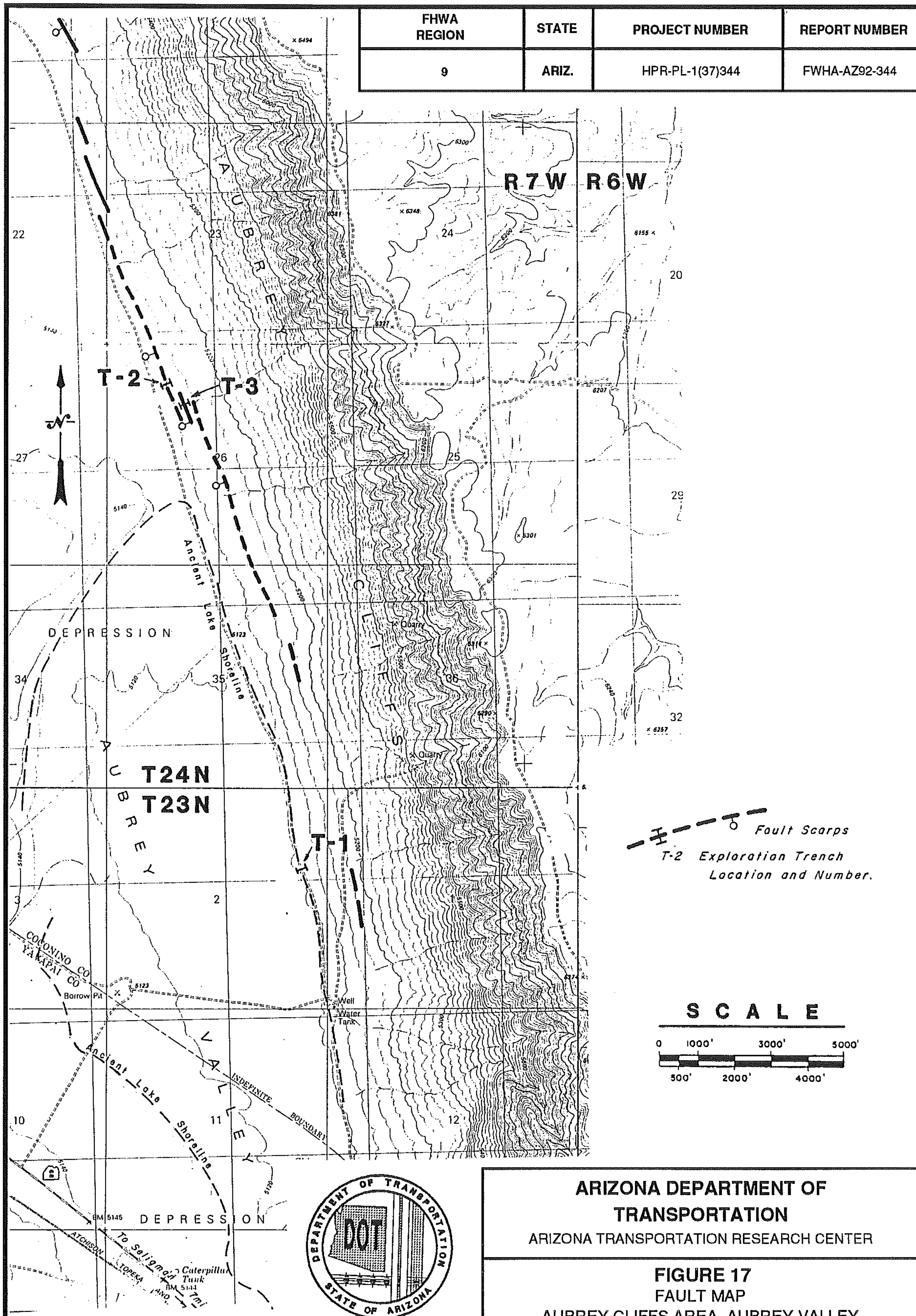

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FIGURE 17
FAULT MAP
AUBREY CLIFFS AREA, AUBREY VALLEY

in northwestern Arizona has a very linear trace, but one that has very distinct changes in orientation. The southern part of the fault strikes northwesterly. About half-way between Seligman and Frazier wells, the fault bends to the northeast; at the northern end, the fault bends again and strikes northerly. Menges and Pearthree (1983) noted these trends and designated three segments, the Southern, Central, and Northern. At the northern end of the northern segment, the fault appears to merge with a prominent east-west trending ridge that appears to be fault-controlled and which merges westerly with the Toroweap fault system. A smaller escarpment extends northwesterly from the intersection of the Aubrey fault and the east-west trending fault. Although no scarps were observed in Quaternary sediments, this northerly extension also appears to be fault-controlled and appears to extend to Prospect Graben (#11), another splay fault of the Toroweap fault. This complex surficial fracture pattern is similar to many faults in this part of the state and is believed to be due to neotectonic reactivation of ancient basement faults as discussed by numerous other geoscientists (for example, Shoemaker et al, 1978; Young et al, 1987; Hamblin and Best, 1979). Reversal of ancient fault displacement along the Aubrey system is evident near milepost 135 at the southern end of the fault (Young et al, 1987).

Aerial reconnaissance, aerial-photograph analysis, and preliminary ground reconnaissance performed during this investigation suggests that Aubrey Cliffs are a fault-line scarp rather than a true fault scarp. The strong alignment of truncated ridge spurs at the base of the cliffs that appear to mark the location of the fault (Figure 18) is probably a result of nearly horizontal, erosion-resistant Paleozoic strata cropping out along the base of the cliffs below a sequence of softer, less competent strata. In other words, the Aubrey Cliffs might represent a laterally retreating erosional remnant of the principal fault scarp which is recognized by subtle scarps in alluvium about two-thirds of a mile west of the base of the cliffs (Figures 17 and 18). This alluvial fault scarp occurs only along the southern segment of the Aubrey fault system. Alternatively, the escarpment could reflect an older parallel fault that has not ruptured since about middle Pleistocene time. The central and northern segments do not have any good evidence of late Quaternary displacement other than the strong linearity of the cliffs. Although the possibility of a fault being located directly at the base of the cliffs cannot be ruled out and the linearity does suggest control by Quaternary faulting, any alluvial scarps created by fault displacement must have been eroded away. Just how long it might take to remove all trace of such a scarp depends on several factors (height of scarp, climate, erosional regime, resistance to erosion etc.). Scarps in the drier climates of southeastern Arizona are still visible after about 80,000 to 100,000 years; if the rates of erosion are similar in the Aubrey Valley area, the central and northern segments of the Aubrey fault have not suffered any surface rupture in late Pleistocene time (i.e. about the past 100,000 years).

Long periods of inactivity are consistent with the appearance of the Quaternary fault scarps along the southern segment of the Aubrey fault which are very degraded, highly dissected, and rounded. The degree of degradation and low scarp-slope angle, when compared to other scarps in the Basin and

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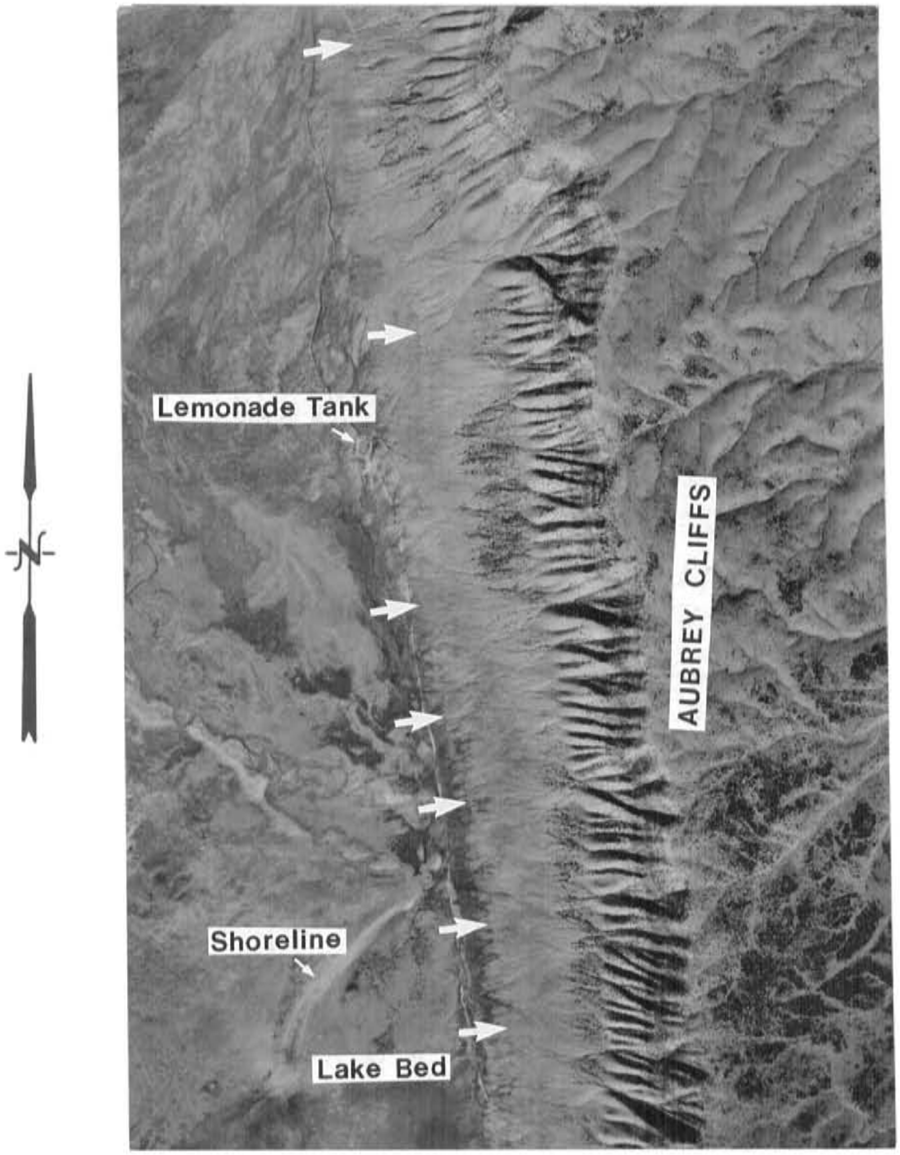

SOUTHERN AUBREY VALLEY; AUBREY CLIFFS ARE ON EAST. WHITE ARROWS INDICATE LOCATION OF QUATERNARY FAULT SCARPS AND LINEAMENTS.

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FIGURE 18
AERIAL PHOTOGRAPH OF AUBREY FAULT

Range province, suggest an age for the latest surface displacement of about 20,000 to 30,000 years before present.

(c) **Trenching:** To evaluate the age and earthquake potential of the Aubrey fault, trenches were excavated across the trace of the southern segment of the fault (Figure 17). Aerial reconnaissance indicated several short, prominent to subtle scarps at the northern end of the south segment just south of Rhodes Canyon. Subsequent field inspection revealed that the alluvial fan gravels along the more prominent of these scarps was thin and underlain by hard Paleozoic-age bedrock. Such hard layers cannot be easily trenched and it was not likely that Paleozoic strata would provide any useful information on neotectonic faulting so these scarps were not considered for trenching. Instead, the trenching activities were conducted across the more-subtle alluvial scarps farther to the south (Figure 17). The trenching methods employed were the same as those discussed in the description of the Big Chino fault (Section 3.d.(1),a) and are not repeated here.

Trench 1 was excavated across the highest and most prominent alluvial scarp along the southern segment (Figure 17). This trench revealed that the scarp was not a fault scarp but a shoreline feature related to the late Pleistocene-age lake described above. Trench 1 (Figure 19A and 19B) conclusively showed unfaulted lake-bed clays overlain by alluvial fan gravels indicating that at one time the lake was larger than the extent indicated by the shoreline shown on Figure 17. Re-examination of aerial photographs after trenching revealed extremely subtle, discontinuous, tonal lineations to the

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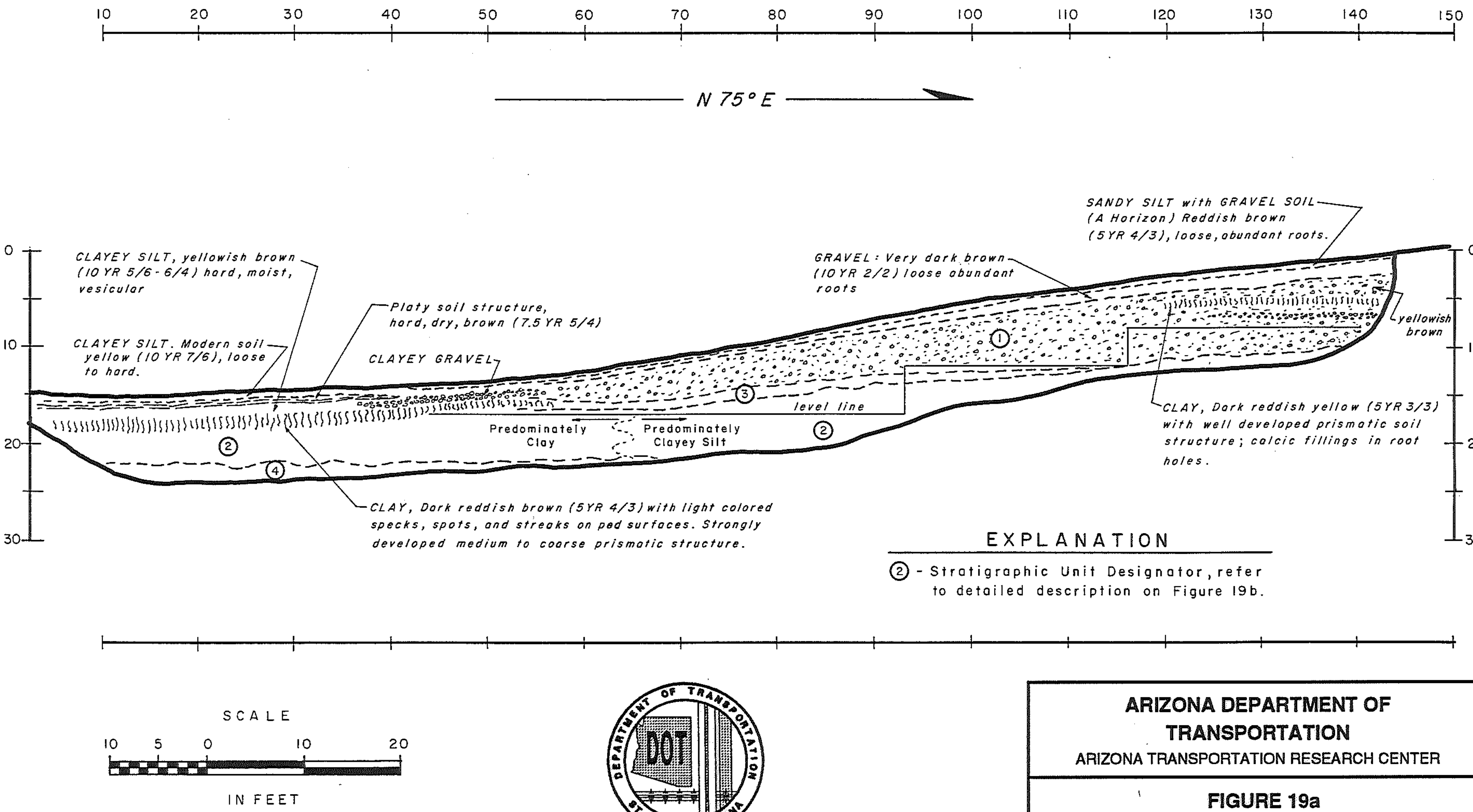

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FIGURE 19a
TRENCH NO. 1 - AUBREY FAULT

FHWA REGION	STATE	PROJECT NUMBER	REPORT NUMBER
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Unit No.	Description
1)	SOIL ARGILLIC B HORIZON: Developed in distal alluvial-fan gravel. Dark reddish brown (5YR 3/4). well-developed clay films on clasts. Most clasts are of pebble size but range from pebbles to small cobbles (1 - 1/2 - inch diameter). Poorly bedded but nearly horizontal attitude is obvious due to lenses of granule-size sand and clayey silt. Several thin layers (about 2 inches) of silty clay with well-developed prismatic soil structure occur northeast of Station 100 (largest one is shown). Hard, dry. Clasts are angular to subangular.
2)	SANDY SILT, CLAYEY SILT, CLAY: Multi-colored and mottled. Generally reddish yellow (7.5YR 6/6 to 5YR 6/6) with pale brown and pinkish white (7.5YR 0/2) and black specks, spots, and lenses. Lighter colors due to pedogenic carbonate. Black is manganese oxide. Clay content increases to southwest; northeast of Station 65 unit is predominantly dry clayey silt; southwest of Station 65 unit is predominantly moist clay, with yellowish red (5YR 4/6) to dark reddish brown (5YR 3/4) colors; hard, massive, with more and larger black spots. Northeast of Station 65, unit is generally hard, dry to slightly moist, and porous. Few pores are lined with $CaC0^{3}$, many have dead roots. Upper part of unit has a few small scattered pebbles, clast content increases with depth. A few short lenses of pebbles and small cobbles occur. Colors darken toward bottom. Contact with Unit 3 is clear but irregular.
3)	CLAYEY SAND: Reddish brown, fine-grained sand. Weak to moderately developed prismatic soil structure in scattered lenses. Upper contact abrupt and moderately smooth. Moist, hard.
4)	SILTY CLAY: Same as Unit 2 but higher percentage (about 20%) of black manganese oxide as spots, streaks, lenses, and small hard nodules. Upper contact diffused and broken.

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FIGURE 19b

TRENCH NO. 1 - AUBREY FAULT

SOIL DESCRIPTIONS

east of the trench location (Figure 17) suggesting that a fault does extend as far south as the T-1 location but is farther to the east.

Trenches 2 are 3 were excavated farther to the north where scarps are minor, discontinuous features generally no more than about 5 to 10 feet high (Figures 20 and 21). Trench 2 did not show conclusive evidence of surface rupture but did reveal warped gravels, strata thickening, and rudimentary colluvial wedges across a narrow zone (Figure 20). These features are interpreted to be from warping of surficial layers by a subsurface fault that did not quite extend to the ground surface at this specific locality. Strongly developed soil horizons in the alluvial deposits comprise reddish A and argillic B horizons (Unit 1) and strongly developed carbonate (K) soil horizons (Units 2 and 3) indicating the deposits are very old. Generally soils with these characteristics are at least 100,000 years old. The degree of soil-profile development in Unit 5 is indicative of a pre Holocene age (10,000 years). Unit 5 is correlative with Unit 1 but has received added influxes of erosional detritus after the warping event forming a cumulative soil that looks much younger than it is.

Although no dateable material was discovered in Trench 2, the soil-profile development and the fault-scarp morphology indicate that the warping event was pre Holocene, and most likely occurred sometime between a few thousand years ago to tens of thousands of years ago (late Pleistocene).

The main fault was well expressed in Trench 3 and displayed evidence of at least two displacements of Pleistocene alluvial gravels (Figure 21).

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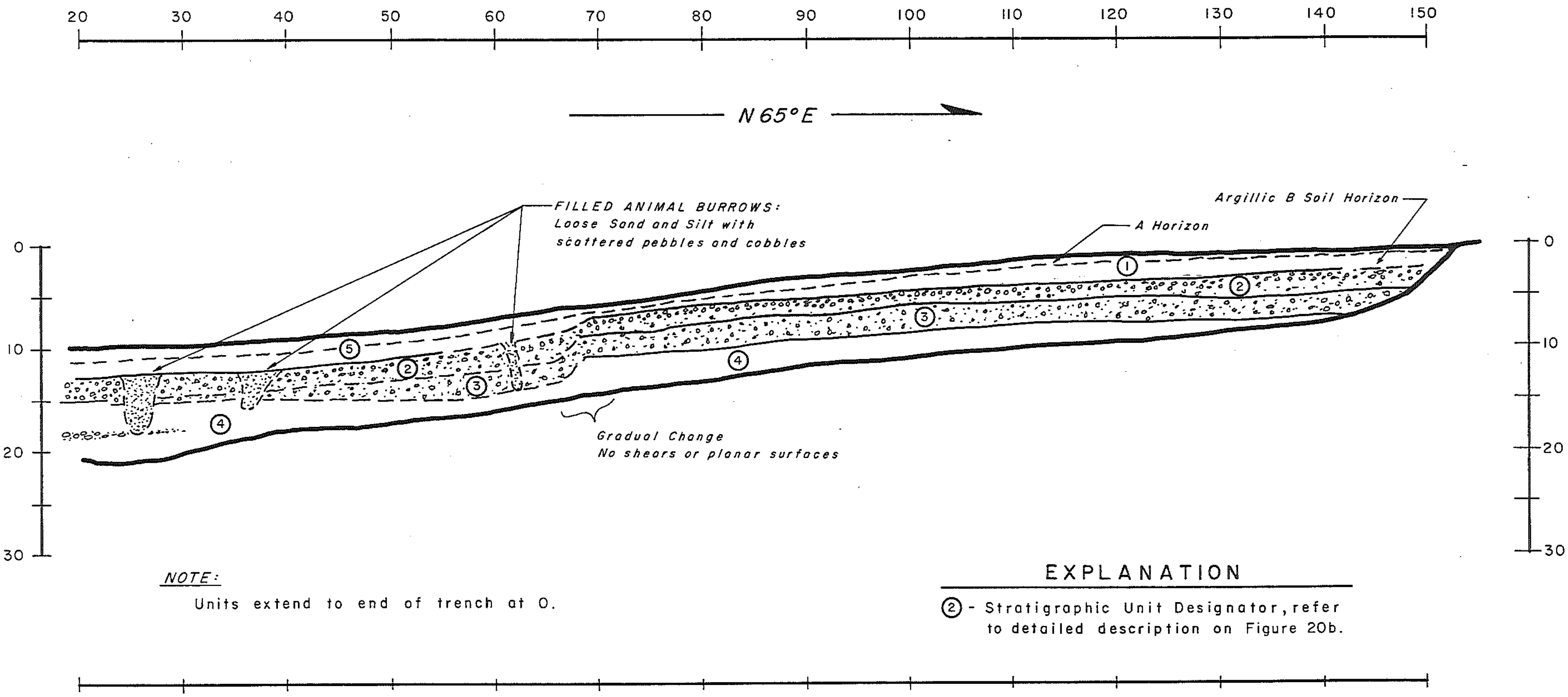

NOTE:
Units extend to end of trench at 0.

EXPLANATION

② - Stratigraphic Unit Designator, refer to detailed description on Figure 20b.

SCALE

10 5 0 10 20

IN FEET

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FIGURE 20a
TRENCH NO. 2 - AUBREY FAULT

FHWA REGION	STATE	PROJECT NUMBER	REPORT NUMBER
9	ARIZ.	HPR-PL-1(37)344	FWHA-AZ92-344

Unit No. Description

1) SOIL, GRAVELLY SILT AND SAND:

   A - Horizon 0 - 6 inches, reddish brown (5YR 4/4), loose.
   B - Horizon dark reddish brown (5YR 3/3);
   Argillic B. Moist.

2) GRAVEL: Pedogenic K Horizon, hard, white, Stage IV; large pebbles and cobbles at top tightly cemented in carbonate, grades downward into pea-sized gravel. Some scattered boulders.

3) GRAVEL: Multi-colored, white to yellowish red (5YR 5/8). Lenses of Stage III K horizons.

4) SILT WITH GRAVEL, dark brown (7.5YR 4/6).

5) SOIL, GRAVELLY SILT AND SAND:

   A - Horizon 0 - 1 ft., brown (7.5YR 4/4) with abundant roots, loose, dry.
   B - Horizon; argillic, yellowish brown (10YR 5/6), hard, dry, moderately developed, medium blocky texture.

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FIGURE 20b

TRENCH NO. 2 - AUBREY FAULT

SOIL DESCRIPTIONS

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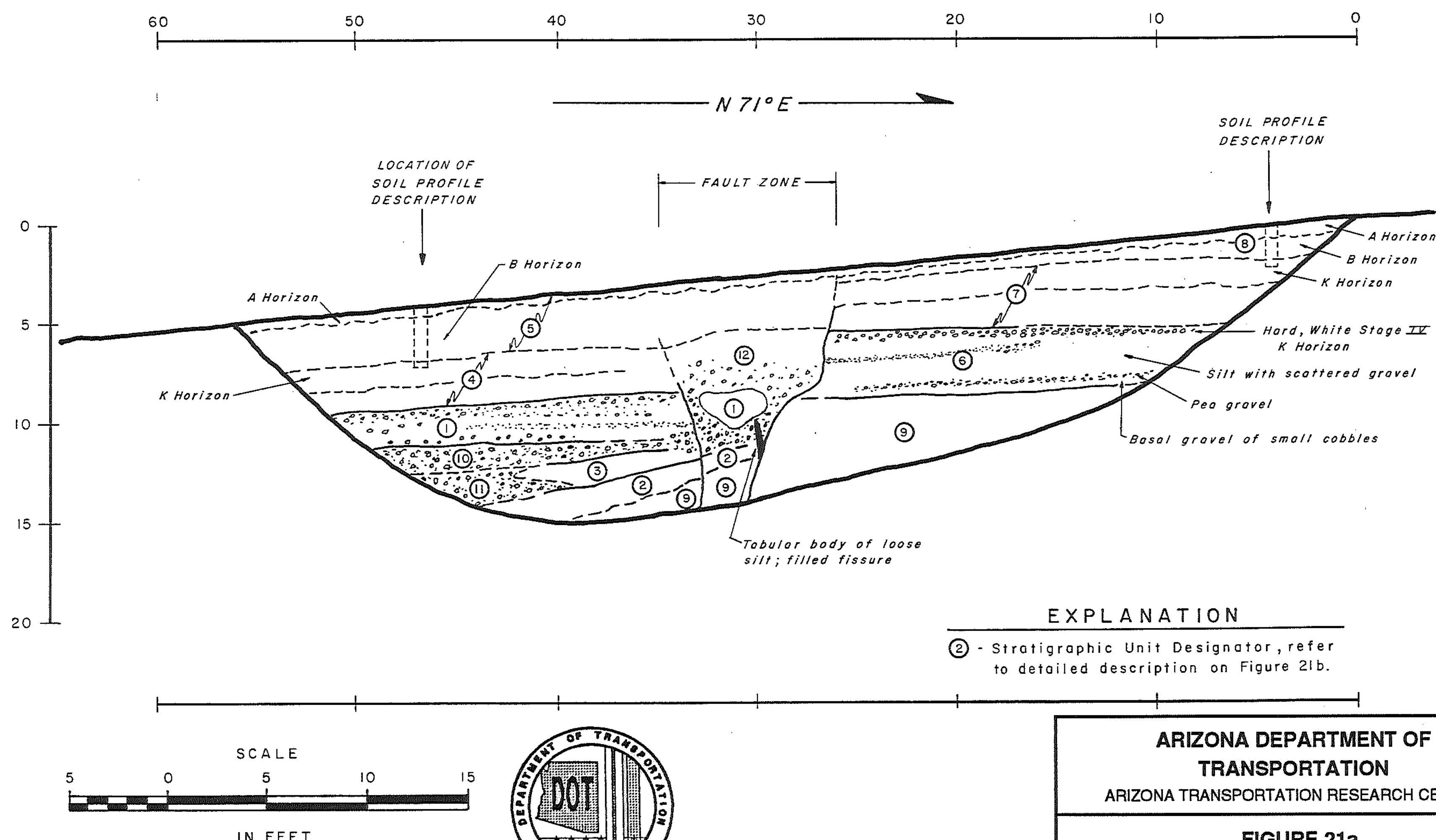

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FIGURE 21a
TRENCH NO. 3 - AUBREY FAULT

FHWA REGION	STATE	PROJECT NUMBER	REPORT NUMBER
9	ARIZ.	HPR-PL-1(37)344	FWHA-AZ92-344

Unit No. Description

1) GRAVEL: Pedogenic K Horizon; white with reddish yellow lenses. Large layer of pebbles at top of unit grades downward into primarily pea-sized gravel at bottom of unit. Pebbles are subrounded to subangular with calcic coatings up to 1/4 inch thick. Hard, dry. Advanced Stage III to early Stage IV. Abrupt, undulating upper contact; clear, undulating lower contact.

2) GRAVEL: Pedogenic K Horizon; white, completely plugged and cemented with CaC03; pebbles completely coated with carbonate. Subrounded to subangular clasts. Hard, dry, Advanced Stage III to early Stage IV. Similar to Unit 6. Gradual, undulating lower contact.

3) GRAVELLY CLAY: Dark reddish brown (5YR 3/3), moist, hard, forms smooth wall. Clear, slightly undulating lower and upper contacts. Grades laterally into gravel of Unit 11.

4) SILT AND SAND LAYERS WITH GRAVEL: Upper 1 to 1.5 feet is hard, white pedogenic K Horizon with advanced Stage III to early Stage IV development. Lower contact of K Horizon is gradual and undulating grading into discontinuous layers, lenses and spots of yellowish red (5YR 5/8) to reddish brown (5YR 4/4) and white silt, sand, and gravel. Becomes less prominent towards fault.

5) CLAYEY SILT AND SAND WITH SCATTERED PEBBLES AND COBBLES (soil developed on alluvial fan deposit):

Horizon	Depth	Color	Structure	Consistency	Boundary	Carbonate
A	0-6"	Strong Brown 7-1/2YR 4/6 Sl. Moist Abundant Roots	fine-med Granules	Loose	Gradual Irreg.	
Bwk_1	6 - 14"	Dark Brown 10YR 4/3 Dry	Medium Subang Weak	Mod. Hard	Gradual Irreg.	Spot & streaks Thin discont. coating Stage I
Bwk_2	14 - 28"	Yellowish Red 5YR 5/6 Dry 5YR 4/6 Wet	Med blocky Mod	Mod. Hard Plastic Non sticky	Gradual Irreg.	Stage I-II Small nodules; Spots, streaks on peds, thin coatings on pebs Stage 1

Porous; can roll into 1/8" thread and bend with some cracking.

6) GRAVEL/SANDY SILT: Pedogenic K Horizon developed on alluvial fan deposits. Upper 2 - 3 feet is hard, white, Stage IV K Horizon in a pebble gravel. Lower part of unit comprises alternating beds of silt, sand, and gravel, moderately well-bedded with variable degrees of pedogenic carbonate development (generally in Stage III). Generally unit is white but a few pinkish and reddish-yellow lenses occur.

7) SAND AND GRAVEL: Alternating reddish brown (5YR 4/4) to yellowish red (5YR 5/8) and white lenses of sand and gravel. Uppermost 1 to 1.5 feet comprises white, completely plugged incipient Stage IV to advanced Stage III, hard, K Horizon developed in a pebble gravel, clasts are subrounded to subangular with calcic coatings up to 1/2 inch thick on bottom of clasts. Lower part of unit comprises discontinuous to continuous coarse sand-pea gravel and small-cobble gravel beds. Predominant gravel size is pebble and pea size but range up to cobble size. Upper contact clear, undulating.

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FIGURE 21b

TRENCH NO. 3 - AUBREY FAULT

SOIL DESCRIPTIONS

FHWA REGION	STATE	PROJECT NUMBER	REPORT NUMBER
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Unit No. Description

8) SOIL SANDY AND GRAVELLY SILT:

A 0 - 6" Sandy silt with scattered pebbles and cobbles with moderate amount of roots and organic debris. Strong brown (7.5YR 4/6). Slightly moist, loose, granular to moderate fine-medium blocky texture in spots. Non-plastic, non-sticky. Gradual, irregular lower contact.

Bwt 6 - 18" Silty gravel; dark yellowish brown (10YR 4/4) when moist, brown (10 YR 5/3) to yellowish brown (10YR 5/4) when dry. Small calcic nodules, spots, and streaks and disseminated carbonate in lower 12" of unit. Dry, hard; moderate, medium blocky texture. Sticky, plastic. Gradual irregular contacts.

9) SANDY SILT WITH SCATTERED PEBBLES AND OCCASIONAL LENS OF GRAVEL: Reddish brown with scattered calcic specks and streaks. Hard, dry, friable.

10) GRAVEL: Reddish brown. Primarily pebble size with scattered small cobbles. Subrounded to subangular clasts.

11) GRAVEL: Reddish brown. Primarily pebble size with scattered small cobbles. Subrounded to subangular clasts. Abrupt, slightly undulating lower contact.

12) GRAVEL/SILT/SAND: Reddish brown (5YR 4/6) to dark brown (7.5YR 4/4). Loose, structureless mixtures of sand, silt and gravel. Gravel sizes range from pebbles to small boulders. Looser with depth.

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FIGURE 21b (cont'd.)

TRENCH NO. 3 - AUBREY FAULT

SOIL DESCRIPTIONS

Units 4 and 7 represent the same stratigraphic unit offset by the fault, as are units 1 and 6. Both of these units have advanced soil-profile development which must have required several tens of thousands of years to develop on each unit. Unit 2 has similar advanced development of pedogenic carbonate which also must have taken several tens of thousands of years to develop. The total time represented by these stratigraphic units appears to represent a large portion of the late-Pleistocene Epoch and might be as old as middle Pleistocene. These relationships indicate that even though there has been recurrent displacement along this fault, the recurrence intervals between events are long and the rate of slip is very slow.

To get a better estimation of the ages involved, a scenario of faulting, erosion, deposition, and soil development is postulated by correlating the major soil horizons to the marine oxygen-isotope chronology of Shackleton and Opdyke (1973). Figure 22 is a diagrammatic reconstruction outlining the sequence of major events interpreted from the wall of Trench 3. On Figure 22, the glacial and interglacial stages refer to the oxygen-isotope stages. The illustrations may appear to represent more-conclusive interpretations than is really intended. Some of the ages given in the scenario may have uncertainties as large as 50 percent. Correlation to the glacial stages suggests that the latest fault rupture occurred about 30,000 years ago and the previous event occurred between about 100,000 and 200,000 years ago.

(d) **Fault displacements:** The total displacement associated with these events is about 6 feet suggesting a slip rate of about

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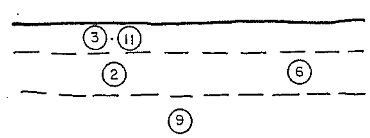
A APPROXIMATELY 200,000 YEARS BP

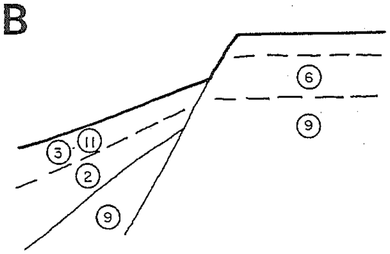


DIAGRAMMATIC SKETCHES - NOT TO SCALE

UNIT 2/6 AND PERHAPS 3/11 DEPOSITED DURING THE COOL WET CLIMATE OF GLACIAL STAGE 8 (>250,000 BP).

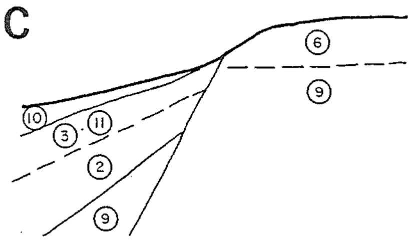
SOILS FORM ON THE UPPER PART OF UNITS 2 AND 6 DURING THE DRY WARM INTERGLACIAL STAGE 7 (250,000-200,000 BP). K HORIZON DEVELOPS TO STAGE III/IV.

B



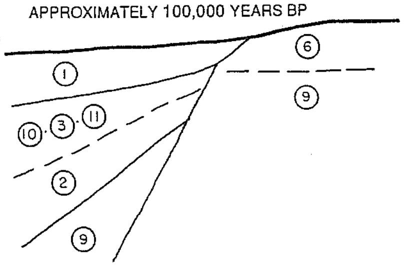
DISPLACEMENT 1 OCCURS (2.5 FT DISPLACEMENT), UNITS 2, 3, AND 9 ARE DOWNFAULTED AND TILTED.

C



THE FAULT SCARP IS ERODED RESULTING IN DEPOSITION OF UNIT 10 AS COLLUVIAL WEDGE AT BASE OF SCARP. UPPER A/B SOIL HORIZONS OF UNIT 3/11 ARE STRIPPED AWAY BY EROSION. SOIL DEVELOPMENT BEGINS ON UNIT 10 AND REACHES A MODERATE DEGREE OF DEVELOPMENT DURING A TIME INTERVAL OF A FEW THOUSAND YEARS (5,000 TO 15,000 YRS).

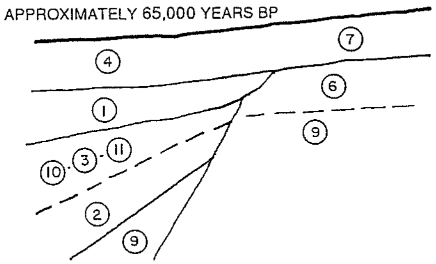
D APPROXIMATELY 100,000 YEARS BP



UNIT 1 AND NEW PART OF UNIT 6 ARE DEPOSITED DURING COOL, WET, STAGE 6 GLACIAL PERIOD (125,000-195,000 BP).

SOIL FORMS ON UNIT 1 DURING DRY, WARM, STAGE 5 INTERGLACIAL PERIOD (75,000-125,000 BP). UNIT 1 ACQUIRES STAGE III/IV K HORIZON; EXISTING K HORIZON ON UNIT 6, ALREADY WELL DEVELOPED FROM PREVIOUS CYCLE, CONTINUES TO DEVELOP.

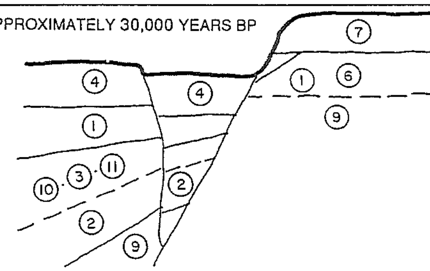
E APPROXIMATELY 65,000 YEARS BP



GLACIAL STAGE 4 BEGINS, UNIT 4/7 IS DEPOSITED (65,000-75,000 BP).

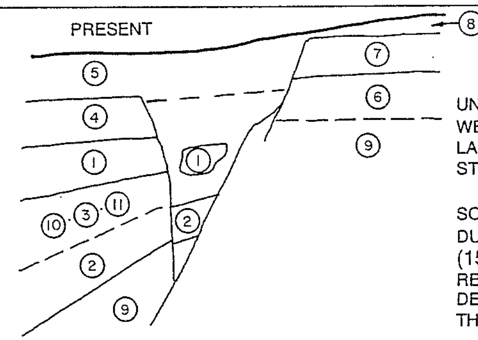
SOIL FORMS ON UNIT 4/7 DURING INTERGLACIAL STAGE 3 (30,000-65,000). SOIL-FORMING EPISODE IS LONG ENOUGH TO DEVELOP STAGE III/IV K HORIZON, AN INTERVAL REPRESENTING MOST OF STAGE 3.

F APPROXIMATELY 30,000 YEARS BP



SECOND DISPLACEMENT OCCURS, OFFSETTING UNITS 4/7 AND 1/6, AS WELL AS ALL OTHER EXISTING UNITS, ABOUT 3 FEET.

G PRESENT



UNIT 5 IS DEPOSITED AS COLLUVIAL WEDGE/GRABEN FILL WITH EOLIAN AND LAKE INFLUENCES DURING GLACIAL STAGE 2 (15,000-30,000 BP).

SOIL FORMS ON UNITS 5/8 DURING INTERGLACIAL STAGE 1 (15,000 TO PRESENT). TIME REQUIRED FOR THIS DEGREE OF SOIL DEVELOPMENT REPRESENTS MOST OF THE PERIOD (I.E., >15,000 YEARS).

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FIGURE 22
FAULTING SCENARIO, AUBREY FAULT

0.01 mm/yr. This is a very slow rate. The surface trace of the southern segment is characterized by several short, en echelon scarps and lineaments (Figures 17 and 18) indicating the faulting is occurring over a broad zone, possibly along sub-parallel faults rather than on one distinct sharp break. The presence of other subparallel scarps and lineaments would suggest that displacement may be partitioned over more than one fault splay and that the rates determined from Trench 3 may not be representative of the total rate for the entire Aubrey fault system. Even though there was no evidence of surface rupture in Trench 2, the ground surface was still displaced about 2 feet. The total slip rate must also account for these apparent displacements in Trench 2, as well as the scarps near Rhodes Canyon which are much larger. The scarps near Rhodes Canyon are up to 15 to 20 feet high. If the total late-Pleistocene displacement is similar to the height of the scarp, the slip rate would be about 0.03 mm/yr.

(e) Earthquake Potential: As discussed above in Subsection (b), the Aubrey fault may consist of several discrete segments and as such is not likely to experience rupture of its entire length during any one event. The total length of the fault, from the south end to the Toroweap fault is about 48 miles. The two most prominent segments, the Southern and the Central, each are about 17 to 18 miles long.

The latest surface rupture, as indicated by alluvial scarps and trenching, was about 12 to 15 miles long. Based on comparison to empirical data, such a rupture length with an average displacement of 3 feet would have been associated with about a magnitude 6.6 earthquake.

Estimates of the maximum credible earthquake based on empirical data such as Slemmons (1982), Bonilla et al (1984), Wyss (1979), and moment-magnitude calculations suggest that the fault is capable of generating an earthquake in the 6.8 to 7.1 magnitude range. For the seismic hazard analysis, the MCE is estimated to be 7.25. Based on age estimates from the trenches, such events appear to be extremely rare and occur only about once every 100,000 years or more.

(f) **Summary:** In summary, trenching investigations of the Aubrey fault have shown that the fault has had recurrent activity in late Quaternary time with the latest displacement occurring about 30,000 years ago and a previous displacement at least 100,000 to as much as 200,000 years before that. These ages suggest long-term average recurrence intervals of at least 100,000 years and slip rates on the order of 0.01 to 0.03 mm/yr. The maximum credible earthquake is estimated to be about 7.25.